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A review of subtidal benthic habitats and invertebrate biota of the Strait of Georgia, British Columbia

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5 ***Strait of Georgia, British Columbia***

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## 32 **Abstract**

33  
34 The initial phase of a collaborative Ambient Monitoring Program (AMP) for the Strait of  
35 Georgia (SoG) (Marine Environmental Research Vol. x, pp. ) has focused on the benthos,  
36 sedimentary regimes, organic and contaminant cycling in subtidal regions of the strait. As part  
37 of that project, we review the primarily subtidal benthic invertebrate faunal communities found  
38 in the SoG, with particular reference to habitats and sediment conditions. This topic has not been  
39 addressed in the primary literature for over 20 years. Benthic biota are the baseline sentinels of  
40 the influence of natural and anthropogenic inputs to sediments. They are also a fundamental  
41 component of the food chain at the seafloor, and their community ecology must be clearly  
42 understood in order to predict how anthropogenic activities and climate change will affect our  
43 coastal oceans. The purpose of this review is to provide context on habitats and biota in the SoG,  
44 and to highlight topics and geographic areas where our knowledge of the benthos is limited or  
45 lacking.

46  
47 **Keywords: benthos; Strait of Georgia; subtidal communities; intertidal communities;**  
48 **British Columbia; anthropogenic influences**

## 49 50 **1. Introduction**

51  
52 The introduction (Section 1) includes the background to this review (Section 1.1), plus  
53 overviews of the oceanography (Section 1.2) and sedimentary regimes (Section 1.3) of the SoG.  
54 Section 2 reviews information available on the SoG's benthic habitats and invertebrate

55 communities, with specific sections on intertidal (Section 2.1) and subtidal (Section 2.2)  
56 communities and habitats. Section 2.2 is further divided into subsections based on subtidal depth  
57 range and substrate type. Anthropogenic influences on benthic environments and invertebrates  
58 of the SoG are summarized in Section 3; case studies of each type of anthropogenic influence are  
59 also presented. Section 4 provides a brief summary of the review paper.

60

### 61 **1.1 Background**

62 Sources, and availability, of information for this review depended largely on the depth range of  
63 interest. For example, one source of information on intertidal habitats and biotic conditions for  
64 the SoG includes broad-scale mapping, or monitoring, studies with the purpose of managing  
65 broader geographic regions for multi-user inputs and conservation. Mapping data are limited to  
66 intertidal zone and the shallow subtidal (<30 m) habitats that have broad aerial, or ground survey  
67 coverage. Unfortunately, at depths >30 m, such mapping and survey data do not exist for the  
68 SoG. Rather, information for these depths comes primarily from ship-board sampling as part of  
69 studies designed to address specific questions for limited geographic areas. These studies tend,  
70 therefore, to be focused on a defined area, a specific anthropogenic influence and/or on data  
71 collection in support of fisheries and/or environmental management. Similar sources of  
72 information are also available for intertidal and shallow subtidal (0-30 m) habitats for the SoG.  
73 While most marine habitats are discussed, at least briefly, in this review, the paper was  
74 conceived within the context of a project which was biased towards subtidal, sedimentary  
75 habitats, and hence it is these latter habitats that are the focus of this review.

76

77 In temperate coastal areas world-wide, most benthic biological research and monitoring  
78 programs focus on macrobenthic invertebrates (those captured with  $\geq 500 \mu\text{m}$  mesh screens). For  
79 this reason, macrobenthic invertebrate communities are the main subject of this review. In  
80 addition to size, the life histories, responses to natural and anthropogenic conditions and changes,  
81 and trophic strategies of macrobenthic invertebrates are far better understood and documented  
82 than those of smaller invertebrates and protozoans. For example, many commercially important  
83 macroinvertebrate species live within the sediments (e.g., clams) or on the surface of the  
84 sediments or hard substrata (e.g., crabs). In addition, benthic macroinvertebrates have often been  
85 the subject of antropogenic impact studies; as a result of being largely sedentary, these organisms  
86 are exposed to ambient conditions and may serve as the first-line sentinels reflecting localized  
87 impacts (c.f. Warwick and Clark, 1993; Pohle et al., 2001). It should be noted that many benthic  
88 macroinvertebrates have a pelagic larval development stage and, as a result, are part of an  
89 extensive and intricate food chain which is not limited to the benthos but which can extend  
90 throughout the water column.

91  
92 Benthic invertebrates process the particulate, organic materials (detritus, small organisms) that  
93 are deposited on the seafloor or that are suspended within reach of the organisms, using a wide  
94 range of feeding strategies such as deposit feeding, suspension feeding, filter feeding, or  
95 scavenging. Benthic invertebrates may also be predators, herbivores (grazing on living plant  
96 material) or they may rely, at least partially, on chemoautotrophy via symbioses with bacteria for  
97 their nutrition (Barnes, 1987). Schwinghamer (1983) estimated that, in soft sediments in  
98 temperate coastal regions, macroinvertebrates constitute approximately 95% of the total  
99 invertebrate biomass. Similarly, Rowe et al. (1991) found that in coastal areas in global

100 temperate regions, benthic macroinvertebrates tend to dominate the benthic biomass (excluding  
101 fish) in mid-depth subtidal areas (i.e. below the euphotic zone) followed by the other two major  
102 benthic consumer groups, the meiofauna (interstitial invertebrates sized 42  $\mu\text{m}$  to 1 mm) and the  
103 single-celled organisms (primarily bacteria). While single-celled organisms are beyond the  
104 scope of this review, meiofaunal community studies, where applicable, have been incorporated.  
105 With the exception of foraminifera (for which taxonomy based on shell morphology has been  
106 extensively used in modern and ancient sediments for interpolation of biological and  
107 environmental conditions), however, the availability of information on meiofaunal taxonomy,  
108 life histories, and environmental tolerances is limited.

109 In contrast to diversity and biomass patterns, Schwinghamer (1981) estimates that, because of  
110 their small size, approximately 95% of the total abundance of benthic invertebrates consists of  
111 nematodes and harpacticoid copepods. Included in this total abundance estimate are the larvae of  
112 larger invertebrates and a series of less common phyla, typically captured only by 63  $\mu\text{m}$  mesh  
113 screens, which prey on benthic bacteria, flagellates, ciliates, foraminifera, and diatoms or blue-  
114 green algae in shallower muds (Schwinghamer, 1981; Gerlach et al., 1985). The importance of  
115 meiofauna as the base heterotrophs in the food chain varies depending on habitat type and depth  
116 (Coull and Bell, 1979). Certainly, components of the meiofauna can be very important in  
117 intertidal, and shallow subtidal (i.e. photic zone) benthos where there is considerable primary  
118 production occurring in the sediments (Schwinghamer, 1981, 1983; Rowe et al., 1991).

119 Copepods, in particular, can be a vital food resource for juvenile fish in near-shore nursery areas  
120 (for review see Tito de Moraes and Bodiou, 1984). Harpacticoid copepods in sediment core  
121 samples from *Zostera marina* beds in the Nanaimo River Estuary and the Cowichan Estuary  
122 were diverse (over 50 species from the Nanaimo River Estuary) and abundant (Levings et al.,

123 1983). In contrast to their global findings for mid-depth subtidal coastal areas, Rowe et al.  
124 (1991) suggest that meiofauna may be a more important component of deep subtidal biomass  
125 than are macroinvertebrates. In the SoG, a moderately deep coastal area, it is reasonable to  
126 assume, therefore, that benthic macroinvertebrates are the primary consumers at the base of the  
127 (benthic) food chain and are more important than meiofauna in this regard.

128 The SoG is part of the broader coastal region of southwest BC and northwest Washington State.  
129 Therefore, biological reference materials for the Pacific northwest (e.g. Carefoot 1977; Kozloff  
130 1987) have general applicability to the SoG. The most recently published review of the benthos  
131 of the SoG is Levings et al. (1983). This review included reference to broad-scale, historical  
132 biological surveys from the 1960s and 1970s that were based primarily in intertidal and shallow  
133 subtidal areas; at the time of the review, there was very little available research on mid-subtidal  
134 to deep subtidal benthic invertebrate fauna. These surveys included a few studies of soft  
135 substrate infaunal invertebrates (Ellis, 1967a, b, 1968a, b, c) and descriptions of an extensive  
136 trawl survey of larger epifauna (Bernard 1978). A general description of fjord cliff fauna, based  
137 on submersible surveys from three contiguous fjords, was also included in the review of Levings  
138 et al. (1983). Although not included in the subject matter of this review, intertidal research on  
139 algal and marine vascular plant communities in the SoG was reviewed by Levings et al. (1983)  
140 and, more recently, by Watson (1998). In addition to the general lack of research on subtidal  
141 invertebrate fauna, Levings et al. (1983) point out that there were no data at all from the deep  
142 basin of the SoG and also that little was known about the type, source or composition of  
143 sediments, or sedimentation rates, in the SoG. In the past twenty-five years, a great deal of effort  
144 has been expended to map biophysical conditions in the substrates of the intertidal and shallow  
145 subtidal zones in the SoG; this information is reviewed in Sections 2.1 and 2.2. However, this

146 review concentrates, primarily, on the less accessible and less well understood, subtidal regions  
147 of the SoG.

148 From 1986 to 1992, a series of primarily deeper (>30 m) subtidal benthic surveys were  
149 conducted by the Canadian Department of Fisheries and Oceans and Environment Canada in the  
150 SoG and surrounding areas (Burd and Brinkhurst, 1990; Cross and Brinkhurst, 1991; Burd and  
151 Brinkhurst, 1992). Only one study, carried out in Boundary Bay, conducted both intertidal and  
152 shallow subtidal benthic surveys (Burd et al., 1987). These surveys were briefly referred to in  
153 Brinkhurst et al. (1994) and Watson (1998). The original data, and a meta-analysis for these  
154 coastal surveys, are provided in Burd (1992). Wilson et al. (1994) edited a trans-boundary  
155 (Canada-USA) symposium report reviewing the marine environment and biota of the SoG, Puget  
156 Sound and Juan de Fuca Strait. Several research papers from this report are included in this  
157 review. A broadly based trans-boundary trawl survey of macroinvertebrates and bottom fish  
158 species, which included the southern SoG (Canadian and US), was conducted in 2001 by the  
159 Washington State Department of Fish and Wildlife (Palsson et al., 2003). Although 117 taxa of  
160 large invertebrates were enumerated from trawls, the focus of the survey was on fish stocks,  
161 historical trends, and exploitation rates. However, the distributions of commercial invertebrates  
162 (notably Dungeness crab and pandalid shrimp) were highlighted.

163  
164 Aside from a small number of government studies focused on historical environmental issues  
165 (e.g. the Britannia Mine in Howe Sound (G3 Consulting, 2003; Hagan et al., 2004; Levings et al.,  
166 2004; Zis et al., 2004), the remaining benthic subtidal habitat and invertebrate sampling has been  
167 carried out, primarily, as part of monitoring programs (data collection either for establishing a



168 baseline or as part of an ongoing program) related to specific anthropogenic inputs into the SoG  
169 or its fjords.

170

171 Much of the benthic infaunal data available from the SoG since 1986 has been collated into a  
172 taxonomically coded and consistent meta-database which includes data from background (or  
173 reference) areas, data from areas of known anthropogenic input, and accompanying sediment  
174 physical and geochemical data (Burd et al., in press). Burd et al. (in press) also provide a  
175 detailed discussion of the biotic responses of benthic invertebrate communities in the SoG to  
176 sedimentation rate and organic flux.

177

## 178 **1.2. Oceanography**

179 The oceanography of the SoG, and a number of surrounding fjords and inlets, is described by  
180 Thomson (1981), LeBlonde (1983), Crean et al. (1988), and Stacey et al. (1991), with updates by  
181 Thomson (1994, 1998), Li et al. (1999), and Masson and Cummings (2004). Early numerical  
182 tidal current models for the SoG were reported by Thomson (1981) and Crean et al. (1988); more  
183 recent tidal current models are described in Foreman et al. (1995, 2004). Models of current  
184 variability due to wind, river discharge (estuarine circulation), winter cooling and other non tidal  
185 factors, as well as bio-physical aspects of the water column variability, are currently being  
186 developed by scientists at the University of British Columbia, (through the STRATOGEM  
187 project (<http://www.stratogem.ubc.ca/>), the University of Victoria (VENUS project;  
188 <http://www.venus.uvic.ca/index.html>) and the Canadian Department of Fisheries and Oceans  
189 Institute of Ocean Sciences (IOS) (Masson and Cummings, 2004).

190

191 The SoG is 222 km long and approximately 28 km wide with a mean depth of roughly 155 m  
192 (Thomson, 1981; Davenne and Masson, 2001). Additional characteristic features of the SoG,  
193 taken from England et al. (1996), Thomson (1998), and Thomson and Foreman (1998) are  
194 summarized in Table 1. Fig. 1 shows the depth topography, sills and surrounding inlets of the  
195 Strait.

196  
197 The two primary components of circulation in the SoG, and the dominant factors determining the  
198 rate of basin flushing and exchange, are the diurnal and semidiurnal tidal currents and the  
199 seasonally variable estuarine circulation driven by fresh water fluxes into the strait. The strength  
200 of estuarine circulation in the SoG is affected seasonally by the volume of runoff discharge from  
201 the major rivers (mainly the Fraser River) which enter mostly in late spring to early summer,  
202 with a secondary surge in late fall. Estuarine circulation is strongly affected by the intensity of  
203 vertical tidal mixing which becomes maximal in the narrow channels leading into the strait.  
204 Winds, surface heating and cooling, intrusions from adjoining Juan de Fuca Strait and Discovery  
205 Passage, and variations in offshore oceanic conditions also affect the circulation in the strait.  
206 Other factors influencing the circulation are the shape of the coastline and slope of the bottom  
207 topography, bottom and internal friction, inertial forces and external factors related to up-strait  
208 propagation of oceanic “events” originating over the outer continental margin. These factors are  
209 discussed in Thomson (1998) and outlined in detail in Griffin and LeBlonde (1990), Thomson  
210 (1994), and Thomson et al. (2007). Detailed discussion on the estuarine circulation in the SoG  
211 can be found in Marinone and Pond (1996), Li et al. (1999), Pawlowicz (2001) and Masson  
212 (2002).

213

214 There are a number of distinct oceanographic regimes in the SoG (Thomson, 1998). These  
215 include the three main basin oceanographic regimes (delineated in Fig. 1) that are described by  
216 Thomson (1981, 1998) as follows:

- 217 1) the Southern SoG, which has vigorous flow exchange and mixing between the  
218 southern channels (Haro Strait and Rosario Strait) and the main body of the Strait;
- 219 2) the Central SoG, which extends northward to the southern end of Texada Island,  
220 and receives the main volume of fresh water from the Fraser River runoff; and
- 221 3) the Northern SoG, which occupies the northern portion of the Strait (from the  
222 southern end of Texada Island northwards) but excludes the margin along the eastern side  
223 of Vancouver Island where the water properties appear to be strongly affected by the  
224 southward density jet entering through Seymour Narrows on the flood tide.

225  
226 Connecting oceanographic regimes include Juan de Fuca Strait, which extends from the Pacific  
227 continental shelf to the entrance to the southern end of Haro and Rosario straits (two tidally  
228 active channels with very similar temperature and salinity structure (Thomson, 1998). The  
229 northern end of the SoG is connected to the Pacific Ocean through Discovery Passage and  
230 Johnstone Strait (Harrison and Yin, 1998). These oceanic connections at the northern and  
231 southern ends of the SoG have strong tidal flow and intense turbulent mixing, which is further  
232 enhanced through the narrow adjoining channels (Thomson, 1981). At the southern end of the  
233 SoG, for example, a complex topography of islands and sills creates strong vertical and lateral  
234 tidal mixing (Masson and Cummings, 2000; Pawlowicz, 2002; Thomson et al., 2007), which is  
235 also evident in the vertically mixed particulate distributions in this region (Johannessen et al.,  
236 2005b). There is nominal surface outflow at both ends of the SoG, with approximately 85-95%

237 of the flow volume through Haro and Rosario straits and the remaining flow through Johnstone  
238 Strait. Thomson (1981) examined the cross-sectional areas of all channels leading into the SoG  
239 and found that the southern channels account for 93% of the cross-sectional area and the  
240 northern channels only 7%. The major inlets adjoining the SoG are Burrard Inlet, Howe Sound,  
241 Jervis Inlet (including Sechelt Inlet), Bute Inlet and Saanich Inlet (Harrison and Yin, 1998).  
242 Knight Inlet and Toba Inlet connect through a northern island-strewn archipelago, so can be  
243 considered a separate oceanographic regime. Surface outflow of riverine water strongly affects  
244 the water property structure in this region (Thomson, 1998).

245  
246 The southern SoG is defined as the area extending south from the main arm of the Fraser River  
247 to the eastern end of Juan de Fuca Strait (Thomson, 1981; Harrison and Yin, 1998; Thomson,  
248 1998). This oceanographic regime is dominated by the Fraser River plume when it moves  
249 southward (e.g. during northwest winds and an ebb tide) and is significantly influenced by tidal  
250 mixing over the shallow sills of Rosario and Haro straits during spring tides. Tidal mixing  
251 injects nutrient-rich water into the southern Strait which lessens the occurrence of nitrogen  
252 limitation episodes in the summer. It is, therefore, considered a highly productive area even  
253 though it has not been well studied (Harrison and Yin, 1998). Haro Strait, which separates the  
254 southern Gulf Islands and Vancouver Island from the San Juan Islands, is the most important of  
255 these channels. The flow exchange through this channel is strongly three-dimensional, with  
256 variation over multiple time scales (Pawlowicz, 2002). The exchange undergoes marked  
257 variability at fortnightly, monthly and seasonal time scales due to corresponding variations in the  
258 intensity of the tidal mixing in the channels (i.e., the hydraulic control mechanism outlined by  
259 Griffin and LeBlonde, 1990). During the neap tide portion of the fortnightly cycle, when the

260 tidal currents in Haro Strait are minimal, surface brackish waters from the SoG are able to  
261 “slide” seaward over the more dense oceanic waters entering at intermediate to near-bottom  
262 depths from Juan de Fuca Strait. In summer (July to October), the deep estuarine inflow in Juan  
263 de Fuca Strait carries warm, salty (high density), low-oxygen, high nutrient water inward from  
264 the coastal ocean. This water is then able to penetrate to the bottom of the SoG in a series of  
265 monthly pulses, renewing the deep water nutrient levels in the region; in winter (November to  
266 March), this subsurface inflow occurs only to intermediate depths (Masson and Cummings,  
267 2004). Deep water oxygen levels are increased during deep water intrusions of cold highly  
268 oxygenated water in spring. During the spring tidal portion of the fortnightly cycle, when tidal  
269 currents are maximal, turbulent vertical mixing in Haro Strait and other passages prevents the  
270 simple exchange of brackish SoG water with deeper oceanic water. In this case, there is a reflux  
271 of water from the passages back into the SoG at intermediate depths. Additional details on the  
272 exchange processes through Haro Strait are found in Griffin and LeBlonde (1990), Thomson  
273 (1994), Pawlowicz (2002), Masson and Cummings (2004), and Thomson et al. (2007).

274  
275 The central SoG is defined herein as the area from the south end of Texada Island to a line  
276 drawn from Point Roberts to the Saanich Peninsula (Waldichuk, 1957; Thomson, 1981, 1998).  
277 This oceanographic regime is complex due to the seasonal influences of the Fraser River plume,  
278 which is characterized by low salinity, very high light-extinction coefficients, high  $\text{SiO}_4^{-4}$ , low  
279 chlorophyll and low primary productivity. During freshet, the sediment-laden surface plume is  
280 2-10 m thick (Thomson, 1981), thus reducing the depth of the euphotic zone and primary  
281 production within the surface waters, while greatly enhancing primary (Stockner et al., 1979) and  
282 secondary (Mackas and Louttit, 1988) production at the plume margins. Surprisingly,

283 chlorophyll levels and the abundance of zooplankton and fish are frequently high under the  
284 plume (Harrison and Yin, 1998). Bacterioplankton production is greatly enhanced within the  
285 brackish plume water (Albright, 1983). The area of the Fraser River plume undergoes marked  
286 seasonal variability, with the maximum variations in extent, as well as chemical and biological  
287 parameters, occurring in June, at which time the plume can dominate the central SoG. At any  
288 given time, the distribution of the plume is influenced by the stage of the tidal currents (flood  
289 versus ebb tide) and by surface wind speed and direction (Harrison and Yin, 1998). After wind  
290 and tidal mixing, the third largest mechanism for transporting deep nutrient inputs into the  
291 surface layer of the SoG is the entrainment of nitrate-rich salt-wedge water directly into the base  
292 of the Fraser River outflow (Harrison and Yin, 1998). Seasonal cycles in nutrients, chlorophyll  
293 and primary productivity are relatively predictable in the central SoG (Harrison et al., 1983) but  
294 the day-to-day variation is high, with values ranging over one order of magnitude in some  
295 months (e.g. June). Nitrogen limitation frequently occurs in July and August, depending on the  
296 magnitude of the wind events. As a consequence, it is difficult to draw a reliable map of annual  
297 primary productivity for the SoG (Harrison and Yin, 1998). Modelling surface layer  
298 productivity is also a major component of the STRATOGEM project  
299 (<http://web.uvic.ca/~dower/dowerlab/research.html>).

300

301 As with the southern passages, flow through the northern passages of Discovery Passage and  
302 Johnstone Strait is strongly tidal with a pronounced estuarine circulation component driven by  
303 runoff from the Fraser River. Hydraulic processes again modify the fortnightly, monthly and  
304 seasonal exchange of waters through this region. Although the flow dynamics in the northern  
305 passages are similar to those in the southern passages, the flow tends to have a weaker cross-

306 channel component and experiences less variability in water properties due to the greater  
307 narrowness of the channels (Thomson, 1981, 1994). Considerable oceanographic information is  
308 available for this region as a result of current and water property surveys conducted in the region  
309 in the 1970s. For data on currents and estuarine-type circulation see Thomson (1976, 1977),  
310 Huggett et al. (1980), Thomson and Huggett, (1980), and Thomson et al. (1980a, b). Haigh and  
311 Taylor (1991) studied microplankton communities in the northern SoG and determined that,  
312 because of the long wind fetch and weak halocline (relatively little influence of the Fraser River  
313 compared to the southern regions), wind mixing is likely to prolong or prevent pronounced  
314 bloom formation. By late summer, the west side of the SoG is diatom-dominated and more  
315 productive due to a nutrient-rich tidal jet flowing out of Discovery Passage during a flood tide.  
316 The east side is more stratified due to surface heating and a somewhat lower salinity due to the  
317 Fraser River plume (mainly in June and July) (Haigh and Taylor, 1991).

318  
319 The fjords adjoining the SoG represent a separate oceanographic domain due to the relative  
320 isolation of their water masses from the rest of the strait (Thomson, 1998). The mainland fjords  
321 include Howe Sound, Jervis Inlet, Bute Inlet, Toba Inlet, Knight Inlet, and Saanich Inlet (the  
322 latter being the only fjord on the eastern side of Vancouver Island). Toba and Knight inlets are  
323 not always considered to be part of the SoG (Harrison and Yin, 1998). All fjords are separated  
324 from the main basin by sills shallower than the fjord basin. Only Burrard Inlet, discussed later in  
325 this section, lacks a sill and is not a fjord. Behind the sills, the fjords have glacially-carved  
326 basins which are often far deeper than the SoG itself; the deepest fjord basin (700 m) is found in  
327 Jervis Inlet. Tidal and estuarine currents over the sills provide for an exchange of material with  
328 the SoG, including the possibility of intermittent deep-water exchange events dependent on

329 conditions inside and outside of the silled basins. The sill regions are characterized by enhanced  
330 tidal currents due to restricted openings and shallow depths; this is particularly true in Knight  
331 Inlet (Farrow et al., 1983; Tunncliffe and Wilson, 1988) and at the famous Skookumchuk  
332 Narrows opening into Jervis Inlet (Thomson, 1981). However, inlets with especially shallow sills  
333 at the mouth tend to have low bottom currents in the deep basins located behind the sill, which  
334 can lead to stagnation resulting in low dissolved oxygen levels in bottom waters and sediments  
335 (Thomson, 1981). Basic features of basin topography and oceanography for the SoG fjords are  
336 described by D. Stucchi (IOS, Sidney, BC) ([http://www.pac.dfo-](http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/default_e.htm)  
337 [mpo.gc.ca/sci/osap/projects/bcinlets/default\\_e.htm](http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/default_e.htm)).  
338  
339 Saanich Inlet, the best studied of the SoG inlets in terms of sediments (note that this is not true  
340 with respect to physical oceanography, where Knight Inlet is better understood), is smaller than  
341 most of the mainland fjords and has a relatively minor freshwater input but a substantial  
342 freshwater source just outside the sill (Cowichan River). The Inlet has a shallow sill at 70 m  
343 depth and a maximum basin depth of 225 m. Saanich Inlet is unique in that it is the only marine  
344 fjord in the SoG system with bottom water (>120-140 m) that is anoxic for most of the year.  
345 These conditions are due to high primary production, in addition to restricted bottom water  
346 exchange that occurs over extremely limited duration (Gargett et al., 2003). During fall  
347 upwelling conditions, Saanich Inlet bottom waters are oxygenated for a short time interval only,  
348 with anoxic conditions returning rapidly and extensively throughout the deep waters and  
349 sediments (Anderson and Devol, 1973). Fall upwelling in the SoG usually pushes the bottom  
350 anoxic layer up to mid-water depths prior to complete flushing. Deep water renewal in Saanich  
351 Inlet is described in detail by Anderson and Devol (1973).



352  
353 Howe Sound, a fjord located just north of Vancouver, has the second largest freshwater  
354 discharge into the SoG. The Squamish River, along with the Cheakamus River and some input  
355 from the Fraser River plume, creates low surface salinities in the head of the fjord, along with a  
356 strongly stratified water column with moderate oxygen in the top 30 m. These conditions, in  
357 combination with the heavy glacial silt load carried by the Squamish River from May to  
358 September, result in a high, near-surface, suspended silt load and brackish surface layer that  
359 greatly restrict light penetration (McDaniel, 1973; Hoos and Vold, 1975). Similar conditions are  
360 present in other glacially-fed fjords, such as Bute Inlet and Knight Inlet, although fresh water  
361 input is lower in these latter two fjords ([http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/  
362 bcinlets/references\\_e.htm](http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/references_e.htm)). Deep water (>180 m) in Howe Sound tends to be seasonally hypoxic,  
363 with flushing of bottom water occurring at the time of seasonal upwelling (Levings, 1980a, b).

364  
365 Knight Inlet has a maximum depth of 540 m and two basins; the sill to the inner basin is located  
366 at 48 m depth and the sill to the outer basin, at the mouth of the inlet, at 60 m depth. Bottom  
367 water oxygen levels are higher than most of the mainland fjords (~3 ml/L), indicating frequent  
368 renewals and exchange of a large fraction of the deep water ([http://www.pac.dfo-  
369 mpo.gc.ca/sci/osap/projects/bcinlets/knight\\_inlet\\_e.htm](http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/knight_inlet_e.htm)). Bute Inlet has a maximum depth of  
370 650 m, with a relatively deep sill at 370 m depth and good bottom water oxygenation and  
371 renewal. Bute Inlet has two rivers at the head, with mainly glacial sedimentation (D. Stucchi,  
372 [http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/references\\_e.htm](http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/references_e.htm)).

373

374 As noted earlier, the deepest mainland fjord is Jervis Inlet, with a maximum depth of 670 m. The  
375 sill to the outer basin in Jervis Inlet is relatively deep (240 m) and bottom water exchange is  
376 sufficient to maintain reasonable oxygen levels in the deep basin all year. This inlet also has the  
377 lowest freshwater input of all the mainland fjords (D. Stucchi, [http://www.pac.dfo-mpo.gc.ca/sci/  
378 osap/projects/bcinlets/references\\_e.htm](http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/bcinlets/references_e.htm)). The oceanographic energetics of Jervis Inlet are  
379 described by Freeland and Farmer (1980). Haigh et al. (1992) and Taylor et al. (1994) described  
380 the seasonal cycle of temperature, salinity, nutrients, chlorophyll, and phytoplankton species for  
381 Sechelt Inlet, an arm of Jervis Inlet. Sechelt Inlet is composed of the well mixed Skookumchuck  
382 Narrows, and the more stratified waters of the main inlet and Salmon Inlet.

383 Burrard Inlet, composed of Vancouver Harbour, Indian Arm and Port Moody Arm, receives  
384 moderate runoff from the Indian River, with the outer section of the inlet influenced by the  
385 Capilano and Seymour Rivers (Harrison and Yin, 1998). Burrard Inlet is located within the  
386 Greater Vancouver Regional District and is the most heavily industrialized inlet in British  
387 Columbia. The inlet has a maximum depth of 90 m and the main basin, as well as the shallow,  
388 isolated arms, are well oxygenated throughout the year and flush rapidly (Levings and Samis,  
389 2001; Stacey and Pond, 2003). During a large part of the phytoplankton growing season (May to  
390 July), high-silt water from the Fraser River decreases light penetration in the surface layer and  
391 hence, primary productivity is reduced (Harrison and Yin, 1998). Although it does not have a  
392 sill at the mouth, Burrard Inlet does have several constrictions within the Inlet which create high  
393 currents (Thomson, 1981). Partially as a result of the lack of sill, fine silt sediments in the outer  
394 inlet flow out into the main basin of the SoG. Indian Arm, located at the far northeastern end of  
395 Burrard Inlet, is more fjord-like in structure with a 220 m deep basin and a shallow sill (15 m to  
396 25 m).

397

### 398 **1.3. Sedimentary Regime**

#### 399 **1.3.1 Shoreline Description**

400 For the SoG, both the total shoreline length inclusive of fjords (3721 km), and the area of benthic  
401 habitat (substrate) types were estimated by Levings et al. (1983). The authors note that, for their  
402 estimates, data from hydrographic charts on bottom type was sufficiently detailed only for  
403 intertidal and subtidal habitats down to 20 m. The authors use “shoreline” to represent intertidal  
404 and subtidal habitats down to 20 m and note that rocky and sandy shores make up 88% of the  
405 total shoreline length. However, when area is calculated, sand and mud substrates account for  
406 66.8% (832 km<sup>2</sup>) of the total 1245 km<sup>2</sup> of intertidal and shallow subtidal habitats. In contrast,  
407 rocky shores contribute only 320 km<sup>2</sup> or 25.7% to the total area. Using Natural Resources Maps,  
408 Levings et al. (1983) computed subtidal areas at depths >20 m. While only 11% of the subtidal  
409 area of the SoG is in the 20-50 m depth range, approximately 71% of the subtidal area is within  
410 the 50-300 m depth range, encompassing most of the main basin of the Strait, with the majority  
411 of the substrate soft sediments (see Figs. 2, 3). Only 18% of the subtidal area is >300 m deep  
412 and the majority of these areas are in the mainland fjords (Levings et al., 1983).

413

414 Zacharias et al. (1998a) used the BC Physical Shorezone Mapping System (Howes et al., 1993)  
415 as the basis of an analysis that provides an estimate of the total shoreline length of the SoG,  
416 including fjords (4107 km). The SoG’s intertidal length is estimated to be composed of 26%  
417 rocky cliffs, 16% rock with gravel beach, 11% sand/gravel flats, 9.5% rock with sand/gravel  
418 beach and an additional 10 representative types each composing  $\leq 7\%$  of the shoreline; flats are  
419 those areas with slopes  $< 5^\circ$ , while beaches have slopes from  $5^\circ$ - $20^\circ$  or higher (Zacharias et al.

420 1998b). The same authors estimate that the intertidal area of the SoG consists of 34% estuary  
421 wetland, 17% sand/gravel flat, 9% sand/gravel beach and an additional 11 types, each composing  
422  $\leq 6\%$  of the intertidal area.

423

424 A review of marine ecosystem, or habitat, classification systems available for the SoG benthos,  
425 from the intertidal to the deep subtidal areas, is provided by Watson (1998). One of these, the  
426 British Columbia Marine Ecosystem Classification (BCMEC) system, was first developed in  
427 1995 (Zacharias et al., 1998b, <http://ilmbwww.gov.bc.ca/cis/coastal/bcmec/index.html>).  
428 BCMEC uses a tiered hierarchical system to define ecological boundaries for planning and  
429 administrative purposes (Howes et al., 1996). There are 12 ecosections in British Columbia,  
430 based on differences in ocean circulation, mixing, salinity, temperature, primary and total  
431 productivity, continental slope and shelf influence and freshwater influence (Harper et al., 1993a,  
432 b; Howes et al., 1996; Zacharias et al., 1998a). The SoG represents one ecosection, which is  
433 divided into smaller ecounits (ecological regions) based on a combination of five physical  
434 characters: wave exposure, depth, subsurface relief, current regime, and substrate type (Table 3–  
435 Wainwright et al., 1995; Howes et al., 1996; Zacharias et al., 1998a). Salinity and temperature  
436 data were later incorporated at the ecounit level into the SoG ecosection (Zacharias and Howes,  
437 1998), as were stratification and slope (<http://ilmbwww.gov.bc.ca/cis/coastal/bcmec/index.html>).  
438 Depth, current and relief data used to develop BCMEC came from Canadian Hydrographic  
439 Service charts (depth, current, relief) (Lamb and Edgell, 1986; Wainwright et al., 1995), models  
440 (exposure) (Harper, 1995), and Geological Survey of Canada mapping of benthic sediments  
441 (substrate) (see Zacharias and Howes, 1998 for more detail) with intermittent ground-truthing  
442 (Howes et al., 1994; <http://ilmbwww.gov.bc.ca/risc/>). Fig. 2 illustrates the coarse resolution

443 classification of the SoG, based on the system described above and using much of the collected  
444 data from the Provincial Physical Shore Zone Mapping System (Howes et al., 1994).

445

446 The subtidal components of the ecounits (Fig. 2) are based on extrapolation from data on the  
447 intertidal to shallow subtidal zones ( $\leq 20$  m). This method produces a simplistic rendering of  
448 substrate types; the soft substrate areas are typically much more of a mosaic, frequently with  
449 mixtures of mud and sand, than are depicted, for example, in Fig. 2. This simple scheme is not  
450 designed, therefore, to capture the complexity of substrate types, but rather to provide a general  
451 perspective. Much more accurate and detailed information on subtidal slope, topography and  
452 substrate diversity is available from multibeam data (Fig. 3), as well as from collated sediment  
453 core and grab samples from a variety of sources (see Fig. 4). For example, the multibeam data  
454 show the deep subtidal reefs which have been found, using video transects, to be relic (or living)  
455 sponge and coral reefs (Conway et al., 2007; Cook, in press). Similarly, multibeam data have  
456 shown the complex delta structure and sedimentation around the mouth of the Fraser River and  
457 the southern portion of the Strait (Hill et al. in press). Although, the multibeam data is not useful  
458 at shallower depths ( $< 30$  m) (see Fig. 3), in combination with the physical and biological shore  
459 zone data (Howes et al., 1994; Frith et al., 1994), it provides a fairly comprehensive and reliable  
460 overview of the full range of benthic habitat depths in the SoG (Fig. 4) (see Burd et al, in press;  
461 Cook et al., in press; Hill et al., in press; Macdonald et al., in press).

462

463 Figure 4 shows a plot of sediment percent fines (silt+clay  $< 63$   $\mu\text{m}$  particle size) to illustrate  
464 sediment types in the SoG. A more detailed map of the near-shore sediment types around the  
465 Fraser River delta north to Burrard Inlet is shown in Hart et al. (1998). Note that the greater

466 detail in Fig. 4 can aid in identifying localized “anomalies”. For example, coarse sand is evident  
467 around the Iona outfall (source unclear), at sand heads just south of the mouth of Burrard Inlet,  
468 and at the mouth of the south arm of the Fraser River.

### 469 **1.3.2. Sedimentary Processes**

470 The sedimentary regime for the SoG is extremely complex, particularly around the Fraser River  
471 delta and associated areas receiving maximum deposition from the river (see Hart et al., 1998).  
472 Sedimentary features of this area are described in detail by Hill et al. (in press). Sedimentation  
473 rates, organic and inorganic fluxes for the Strait are described in more detail in Burd et al. (in  
474 press). For the sake of simplicity, this section on sedimentary processes divides the SoG into  
475 two equal regions north and south of the deepest part of the main basin (~400 m) which is  
476 located just south of Texada Island. North of this dividing line (which includes the northern  
477 basin regime; Section 1.2), the basin rapidly becomes narrower and much shallower (<200 m)  
478 creating a barrier to bottom-transported particulate material from the Fraser River (Johannessen  
479 et al., 2005b). Sediment characteristics north of Texada Island suggest that Fraser River material  
480 does not contribute to particulate deposition, and that natural sedimentation and organic flux,  
481 mainly from marine detritus, are much lower than in the southern half of the basin (Burd et al., in  
482 press).

483  
484 In contrast to the northern half of the basin, the southern half of the basin (which includes the  
485 central and southern oceanographic regimes; Section 1.2) receives markedly higher  
486 sedimentation (organic and inorganic) (see Macdonald and Crecelius, 1994 for literature review)  
487 which is from the Fraser River (Burd et al., in press). This higher sedimentation is related to  
488 heavier material deposited primarily at the mouth of the river (up to 10 cm/yr–Hart et al., 1998)

489 and transported along the bottom northward along the bank straddling the Fraser River mouths,  
490 as well as down the slopes to deeper areas (McClaren and Ren, 1995; Hodgins and Hodgins,  
491 2000). As one progresses northward from the river mouth, sediments become progressively finer  
492 (see Fig. 4), and show characteristics of declining proportions of Fraser River deposits (Burd et  
493 al., in press).

494

495 However, the high sedimentation rates to the south of the Fraser River are also related to  
496 particulate deposition from the Fraser River plume during freshet. The dispersion patterns of the  
497 Fraser River plume, which can extend 2-10 m down from the sea surface during freshet  
498 (Thomson, 1981), are aerially visible during the summer months and have been tracked in detail  
499 with satellite imagery (Fig. 5). South of the Fraser River, sedimentation may also be related to  
500 upwelled fine sands (glacial material) from the southern Gulf Islands (Johannessen et al., 2006).  
501 This creates a patchy mosaic of mixed sand and silt substrates in the southernmost portion of the  
502 southern half of the Strait (Fig. 4). The sediments of the deep southern portion of the basin that  
503 are most subject to plume deposition are somewhat sandy, but finer in texture than those along  
504 the slope and bank on the east side of the SOG which receive the coarser, bottom-transported  
505 materials from the Fraser River. Therefore, it can safely be said that the southern and northern  
506 halves of the SoG constitute very different sedimentary regimes (see also Johannessen et al.,  
507 2003).

508

509 Boundary areas of high primary production occur in areas of turbulent mixing in the vicinity of  
510 the north and south island chains which constrict the entrances to the SoG (Parsons et al., 1981).  
511 However, the constrictions at both the north and south end of the SoG result in very little

512 exchange of particulates and, therefore, of contaminants which are bound to particulates,  
513 between the Strait and surrounding waters (Macdonald and Crecelius, 1994, Johannessen et al.,  
514 2003). In contrast, however, water-soluble contaminants can spread broadly outside the confines  
515 of the Strait (Macdonald and Crecelius, 1994).

516  
517 Sedimentation in the fjords of the SoG is largely isolated from the effects of the Fraser River.  
518 Within the fjords, sedimenting material may arise from freshwater sources, delta slope failures,  
519 marine detritus and/or terrigenous erosion of the steep surrounding rock cliffs. The mainland  
520 fjords are bounded by the coast mountain range, so that much of the runoff in stream sources is  
521 of glacial origin ([www.pac.dfo-mpo.gc.ca/SCI/osap/projects/bcinlets](http://www.pac.dfo-mpo.gc.ca/SCI/osap/projects/bcinlets)). Material sedimenting  
522 within fjords is typically fine and is trapped within the fjords' basins by the shallow sills at the  
523 mouth (Thomson, 1981).

524  
525 Turbidity in BCs mainland fjords increases as the degree of freshwater and glacial runoff  
526 increases. Turbidity currents originating with delta slope failures at the heads of inlets are likely  
527 responsible for the bottom water turbidity in some inlets (Pickard and Giovando, 1960; Bornhold  
528 et al., 1994). In Knight Inlet, extremely high turbidity and seasonal vertical flux of glacial silt  
529 from the two rivers that discharge into the head of the Inlet result in suspended matter  
530 concentrations  $>100$  mg/L and a delta slope sedimentation rate of  $4$  kg/m<sup>2</sup>/d in summer. As  
531 commonly occurs in the mainland fjords, vertical flux and turbidity in Knight Inlet decrease  
532 progressively down the Inlet (Farrow et al., 1983). In contrast, Jervis Inlet has very low  
533 freshwater input and, thus, has remarkably clear water throughout the Inlet and at all depths



534 ([www.pac.dfo-mpo.gc.ca/SCI/osap/projects/bcinlets/Jervis\\_Inlet\\_e.htm](http://www.pac.dfo-mpo.gc.ca/SCI/osap/projects/bcinlets/Jervis_Inlet_e.htm); observations from the  
535 submersible PICES IV, Burd, unpublished data).

536

537 Sedimentation rates for the main basin of Howe Sound have been estimated at 0.4 cm/yr (Hickin,  
538 1989) and for the area just outside the Sound's sill at 0.4 to 0.78 cm/yr (Johannessen et al.,  
539 2003). Howe Sound has a relatively high freshwater input (Section 1.2) which results in high  
540 levels of glacial, suspended particulates near the estuaries. Sediment types and probable  
541 transport patterns in Burrard Inlet are complex but have been described by McLaren et al. (1993)  
542 and McLaren (1994). Constrictions within the Inlet and high currents create zones of coarse  
543 sand grading to hard substrate beds (Thomson, 1981), and tend to maintain particulates in  
544 suspension throughout the Inlet. Dredging is required to maintain the channel at First Narrows  
545 (near the Lions Gate outfall), suggesting net deposition. Similarly, high net sedimentation rates  
546 (1 cm/yr) in Port Moody Arm necessitate continued dredging of the deep-sea berths (Levings and  
547 Samis, 2001).

548

549 In Saanich Inlet, the majority of the shoreline consists of steep, rocky cliff walls with  
550 embayments consisting of typical mud/sand flats with some eelgrass beds. The BC Provincial  
551 synthesis report for the Saanich Inlet Study initiated in 1994 concisely summarizes the benthic  
552 habitats and sediment types for different sections of Saanich Inlet (BC Ministry of Environment  
553 Lands and Parks, 1996). The information is limited primarily to habitats at depths  $\leq 50$  m  
554 adjacent to the shore; due to the hypoxic/anoxic nature of the deeper basin areas  $>50$  m, biotic  
555 production is limited considerably.

556

## 557 **2. Benthic Habitats and Invertebrate Communities**

558

559 Although this review is concerned primarily with subtidal habitats in the SoG, Section 2.1  
560 provides a brief overview of pertinent studies on the intertidal invertebrate communities and  
561 habitats of the SoG; descriptions of the intertidal invertebrate biota are not included *per se* but  
562 can be found in the references cited. For example, Watson (1998) provides a list, and a short  
563 review, of studies on intertidal benthic community structure studies that were carried out in the  
564 SoG prior to 1997. Major sources of data on the intertidal zone in the SoG, specifically mapping  
565 programs and surveys associated with commercially important species, are reviewed in Sections  
566 2.1.2 and 2.1.3, respectively. The bio-physical structure of the intertidal zone can strongly  
567 influence the habitat type and biota of the subtidal region and, therefore, aids in providing  
568 context for understanding subtidal habitats (Section 2.2).

569

### 570 **2.1. Intertidal Zone**

#### 571 **2.1.1. Intertidal Habitats**

572 In contrast to subtidal habitats, which tend to be more physically predictable, intertidal habitats  
573 are influenced by greater variability in physical factors (e.g. waves, tidal currents, erosion, slope,  
574 light, air exposure, temperature, salinity, sediment stability). Factors that also affect subtidal  
575 habitats, such as tidal currents, can also affect intertidal areas; for example biodiversity tends to  
576 be enhanced in intertidal areas with fast currents (Levings and Thom, 1994). The influence of  
577 these factors, as well as biological factors, can lead to spatial heterogeneity of intertidal  
578 assemblages in what appear to be similar habitats (Dayton, 1971; Denny et al., 1985; Maurer and

579 Aprill, 2007). Section 1.3 describes the estimated proportions of the intertidal zone of the SoG  
580 that are made up of the different habitat types described below.  
581  
582 Levings and Jamieson (2001) assessed the fish habitat significance of the marine riparian habitat  
583 in the SoG. The marine riparian area is defined, by the authors, as the ecotone where aquatic  
584 habitat at higher tides merges into terrestrial habitat (i.e. the supralittoral). Levings et al. (1983)  
585 reviewed intertidal benthic communities in the SoG in relation to habitat type, specifically sand  
586 beaches, rocky shores, mud flats and vegetated areas. The authors provide a list of invertebrate  
587 studies conducted in each habitat type prior to 1982. Several studies on sand beaches, with many  
588 focusing on Boundary Bay, report on a range of invertebrates from macrofauna to meiofauna  
589 (Kellerhals and Murray, 1969; Harrison, 1981; Smith, 1981; Swinbanks and Murray, 1981). The  
590 most extensive mudflats in the SoG, and those most heavily researched in terms of invertebrates,  
591 are in the Fraser River estuary (see Levings et al., 1983) but research has also been carried out on  
592 the mud flat invertebrate communities of the Squamish Estuary (Levings, 1980b) and Vancouver  
593 Harbour (Levings and McDaniel, 1974). In the SoG, there is considerable variation in the slope  
594 and geology of the rocky shores, with corresponding biological changes (Bousfield, 1957;  
595 Levings et al., 1983). Faunal composition in this intertidal habitat type is thought to be  
596 influenced predominantly by these geological factors, in addition to water characteristics, wave  
597 energy and biological interactions (Levings et al., 1983). In their review of research on  
598 invertebrate communities in vegetated intertidal areas, Levings et al. (1983) demonstrate the  
599 importance of algae and eelgrass in structuring these communities.  
600

601 The importance of substrate type and vertical zonation on intertidal community composition is  
602 emphasized in most studies in the SoG (c.f. Stephenson and Stephenson, 1961a, b; 1972). For  
603 example, Burd et al. (1987) concluded that beach assemblages in Boundary Bay, BC are strongly  
604 controlled by sediment grain size. Early synoptic helicopter surveys of rocky shorelines in the  
605 strait are described in Ellis (1966), and the concept of vertical zonation and succession developed  
606 by Stephenson and Stephenson (1972) in the Strait has also been applied locations outside the  
607 SoG in BC (Ellis, 2002, 2003). Rock and gravel habitats are crucial for shellfish species,  
608 especially the recreational and commercially harvested bivalves (Levings and Thom, 1994).  
609 Larval settlement of Dungeness crabs (*Cancer productus*), as well as that of Manila clams  
610 (*Venerupis philippinarum*), tends to be higher in areas of shell hash, gravel or eelgrass  
611 (Thompson and Cooke, 1991; Dumbauld et al., 1993; Levings and Thom, 1994).  
612  
613 Other sources of information on intertidal restoration, conservation and mapping projects in the  
614 SoG include the BC Community Mapping Network (<http://www.shim.bc.ca/>) and  
615 the BC Coastal Eelgrass Stewardship Project ([http://www.stewardshipcentre.bc.ca/](http://www.stewardshipcentre.bc.ca/eelgrass/eelgrassfinalreport12_04.pdf)  
616 [eelgrass/eelgrassfinalreport12\\_04.pdf](http://www.stewardshipcentre.bc.ca/eelgrass/eelgrassfinalreport12_04.pdf)). While invertebrate communities in eelgrass beds in the  
617 SoG have not been studied extensively, there is some evidence that these communities are  
618 biotically more diverse and structurally different than those in nearby bare sediments (Levings  
619 and Coustalin, 1975; Sibert, 1979; Burd et al. 1987; Seacology et al., 2001). The roots and  
620 rhizomes of eelgrass and the tubes of infaunal invertebrates reduce the mobility of a variety of  
621 burrowing species, including polychaetes, bivalves, crustaceans, and some echinoderms  
622 (Brenchley, 1982). Not only is burrowing time increased but hard bodied taxa, in particular, are  
623 restricted by the biogenic structures (Brenchley, 1982). In addition, eelgrass beds are known to

624 provide protection from predators (Heck et al., 1989) and to encourage the settlement of fine,  
625 suspended particulate material, a potential factor in the noted differences in invertebrate  
626 community composition (Fonseca and Fisher, 1986).

627  
628 Considerable baseline environmental information on the intertidal zone of Saanich Inlet was  
629 generated as a result of two proposed foreshore developments: a ferrochromium production  
630 facility in the 1980s (see Rescan Environmental Services, 1988) and, a large-scale residential  
631 development at the site of the defunct cement plant at Bamberton (Williams, G.L. & Associates  
632 Ltd., 1991; Madrone Consulting Ltd., 1993). Neither of the proposed developments came to  
633 fruition, however. An extensive, and more recent, database is available from the sanitary surveys  
634 of clam beaches in Saanich Inlet (see Walker, 1995) and from eelgrass restoration projects in  
635 Todd Inlet (BC Coastal Eelgrass Stewardship project; [http://www.stewardshipcentre.bc.ca/  
636 eelgrass/eelgrassfinalreport12\\_04.pdf](http://www.stewardshipcentre.bc.ca/eelgrass/eelgrassfinalreport12_04.pdf)). Similarly, the Saanich Inlet Seagrass Survey studied 67  
637 locations (40.9 hectares total area) surveying intertidal and shallow subtidal areas; eelgrass was  
638 limited to three areas with soft bottom substrates ([http://www.env.gov.bc.ca  
639 /wat/wq/saanich/siscr.html](http://www.env.gov.bc.ca/wat/wq/saanich/siscr.html)). There is also a wealth of uncollated information on the foreshore  
640 biota of Saanich Inlet from the local shore-keepers surveys (see Section 2.1.2), as well as  
641 unpublished data collected by W. Austin (Khoyatan Marine Laboratory, Sidney, BC).

642  
643 At Boatswain Bank, just north of the Saanich Inlet sill, recent intertidal transect surveys were  
644 done as part of the baseline assessment for a proposed landfall site for the GSX pipeline  
645 (Seacology et al., 2001). This is an area of extensive intertidal eelgrass beds, as well as green  
646 algae (e.g. *Ulva/Enteromorpha*). Such habitats are considered to be important nursery and

647 feeding grounds for juvenile fish and were meant to be avoided by the pipeline drilling rig.  
648 Although the pipeline project did not go forward, the report contains detailed data listing algae  
649 and invertebrates that are commonly associated with sheltered, near shore habitats in southern  
650 BC fjords. The authors describe this ecotype as a typical south-coast, shallow, sloping beach  
651 with mixed cobble/sand/ gravel substrate (Seacology et al., 2001).

652 The intertidal wetlands of the Fraser River estuary cover an estimated 17,000 hectares  
653 (<http://www.env.gov.bc.ca/cdc/>) and are also one of the most biologically productive systems in  
654 Canada (Levings et al., 1983; Kennett and McPhee, 1988; Harrison et al., 1999). Estimated  
655 productivity (based on biomass) for the 14,000 hectares of Sturgeon and Roberts Bank, including  
656 the main mud flats on the outer shores of Lulu Island totals 1440.6 kcal/m<sup>2</sup>, broken down into  
657 vascular plants (eelgrass) (1320 kcal/m<sup>2</sup>), microbenthic algae (diatoms) (65 kcal/m<sup>2</sup>), benthic  
658 organisms (invertebrates) (40 kcal/m<sup>2</sup>), phytoplankton (in water) (15 kcal/m<sup>2</sup>) and zooplankton  
659 plus epifaunal invertebrates (0.6 kcal/m<sup>2</sup>) (Levings, unpublished data). Macroalgae such as  
660 *Ulva/Enteromorpha* are not included in these estimates (Levings, unpublished data) but are  
661 occasionally present (Harrison et al., 1999). Plants clearly make up the greatest bulk of living  
662 material on the mud flats, by far, and likely provide critical habitat and/or food resources for the  
663 benthic invertebrate fauna. The diverse invertebrate fauna are described in Otte and Levings  
664 (1975). Primary benthic production and nutrient dynamics of the delta, as well as the foreshore  
665 area of Boundary Bay at the Canada/US Border (i.e. outside the influence from the Fraser River),  
666 were recently reviewed by Harrison et al. (1999).

667 All the other major estuaries in the SoG are subject to various conservation and restoration  
668 programs, for which information is available from a variety of sources. For example, research on

669 the benthos of the Squamish River estuary was reviewed by Hoos and Vold (1975) and Levings  
670 et al. (1983), with an inventory of research efforts in the estuary basin provided by Hickin  
671 (1992). Research in the Nanaimo River estuary includes a study on the intertidal hyperbenthic  
672 populations (Sibert, 1981) and the relationship between meiofaunal abundance and intertidal log  
673 storage (Sibert et al., 1979). The Nanaimo and nearby Gulf Island marine shorezone areas were  
674 also the focus of rocky shoreline zonation studies by Stephenson and Stephenson (1961a, b;  
675 1972). Reports on the SoG estuaries can also be found on websites, such as that of BC Hydro  
676 ([http://www.bchydro.com/bcrp/reports/lower\\_mainland.html](http://www.bchydro.com/bcrp/reports/lower_mainland.html)).

### 677 **2.1.2. Shore Zone Mapping Programs**

678 The Provincial Biological Shore Zone Mapping (and database) System (Frith et al., 1994) for  
679 British Columbia was designed to integrate with the Physical Shore Zone mapping (Howes et al.,  
680 1994; see Section 1.3) and is based on taxonomic groupings. The boundaries for units and  
681 components in the physical system, based on geomorphological parameters, are used to define  
682 boundaries for species assemblages (bands) in the biological system. A hierarchical coding  
683 system for biota is included and is based on taxonomic groupings. Components are sub-divided  
684 into across- shore areas of common species assemblages termed bands. Bands are defined by the  
685 dominant cover species and the colour and texture of that band visible from aerial videography,  
686 photography, or from ground surveys (Frith et al., 1994). Maps on a fine scale resolution can be  
687 attained at <http://ilmbwww.gov.bc.ca/>. Publications describing the development of this system,  
688 modeled characterization of intertidal communities and regional diversity are cited in Zacharias  
689 et al. (1998a, b, 1999), and Zacharias and Roff (2001).

690

691 The Canadian Department of Fisheries and Oceans began the Shorekeepers' program for  
692 monitoring the intertidal zones of the British Columbia coast in 1996 in response to need for a  
693 new data acquisition program. The program, aimed at involving coastal communities and  
694 fostering stewardship of the coastal zone, was designed for the monitoring of intertidal habitat by  
695 non-professionals. Full details including survey design, field sampling, data acquisition, etc., can  
696 be found in Jamieson et al. (1999). Data from surveys conducted between 1996 and 2005 are  
697 accessible online (<http://www.shim.bc.ca/atlasses/sk/main.htm>). Although the design and  
698 limitations of survey methods for this program tend to produce a bias towards larger macrofauna,  
699 the resulting data set is cumulative and relatively large, which allows comparison of the biomass-  
700 dominant fauna to the physical characteristics used in the BC Shore Zone Mapping System. The  
701 Shorekeepers' program (Fig. 6) provides a refinement to the habitat classification of the BC  
702 system, including not only substrate type but also dominant algal coverage.

703

### 704 **2.1.3 Surveys and Studies Associated with Commercially Important Invertebrates**

705 The BC Shore Zone Mapping Program is also used to assess suitable habitat for invertebrate taxa  
706 with commercial or recreational fishery value. For example, based on species-specific substrate  
707 and habitat preferences, the relative suitability/rating for the success of Pacific oyster viability at  
708 beach locations in SoG can be mapped (Fig. 7). Manila clam suitability shows a very similar  
709 distribution (Fig. 7). The areas of "good" and "medium" viability correspond to sand and gravel  
710 platforms and sometimes the presence of eelgrass (Fig. 7) (<http://ilmbwww.gov.bc.ca/>).

711

712 The BC Clam Atlas was developed as a means of mapping commercial intertidal clam beaches  
713 (Manila, Littleneck and Butter) on the BC coast. The maps, area calculations and historical



714 landings for the SoG area were published by Harbo et al. (1997), and the maps are presently  
715 online ([http://www-heb.pac.dfo-mpo.gc.ca/maps/maps-data\\_e.htm](http://www-heb.pac.dfo-mpo.gc.ca/maps/maps-data_e.htm)). Information on stocks of  
716 these and other clams can also be accessed using the Canadian Department of Fisheries and  
717 Oceans Stock Status Reports and the Fisheries Management Plans for each species. Geoducks  
718 prefer to burrow in sand, silt and gravel from the intertidal to a depth of 110 m (Canadian  
719 Department of Fisheries and Oceans, 2000). Landings in the SoG are minor (less than 1/3 of the  
720 BC total) and most are collected subtidally by divers. Of the three typical intertidal species,  
721 Manila clams are the species harvested primarily from the SoG (Canadian Department of  
722 Fisheries and Oceans, 1999a, b; 2007). The Fisheries Management Plan for Intertidal Clams  
723 suggests that, presently, stocks are healthy but that the commercial trend is toward reduced  
724 landings as a result of reduction in overall effort, lower prices, and increasing alienation of beach  
725 space for shellfish aquaculture tenures.

726

## 727 **2.2. Subtidal Zone**

728 Levings et al. (1983) reviewed the available sources of subtidal benthic biotic data for the SoG  
729 up to that time. Examples of several large, unanalyzed data sources noted in that review include  
730 Ellis (1967a, b, 1968a, b, c), who provided quantitative data (including abundance of “apparent”  
731 species) resulting from comprehensive surveys of the subtidal fauna and sediments from a wide  
732 variety of geographic locations with the SoG. These studies employed similar methodologies  
733 (grab samples) to those used in more recent, similar studies (see Levings et al., 1983; Burd,  
734 1992; Burd, 2006). Bernard (1978) reported the results of an extensive subtidal bottom survey of  
735 invertebrate fauna from the SoG. The author described, but did not enumerate, the dominant  
736 organisms captured primarily by trawling and divided the sampled

737 areas according to depth range and substrate type. Although some grab sampling was carried out  
738 at key locations, the fauna included in Bernard (1978) are primarily epibenthic.

739

740 This section is based primarily on background conditions where anthropogenic impacts are  
741 expected to be absent or limited. Descriptions of subtidal biotic assemblages based on recent  
742 studies are separated by depth range and substrate type in a manner similar to Bernard (1978) but  
743 with two notable differences. First, four substrate types (mud/silt, sand, gravel and rock/cobbles)  
744 are used in Bernard (1978) while here we employ the following five substrate types: mud,  
745 silt/sand, sand, coarse sand/gravel/cobbles and rock (consolidated). Given that trawling was the  
746 main sampling method used in Bernard (1978), it is assumed that the rock substrate in  
747 rock/cobbles is not consolidated; therefore, the gravel and rock/cobbles substrates of Bernard  
748 (1978) are considered equivalent to our coarse sand/gravel/cobbles substrate. Inherent in these,  
749 and similar habitat classification systems, is that mixed habitats will have overlapping biotic  
750 community types. Second, whereas Bernard (1978) described biota from 20-50 m, and 50-100 m  
751 (primarily for logistical reasons related to towed sampling patterns), biota and available  
752 information for the SoG are reviewed herein for 3 depth ranges (see below: 0-30 m, 30-100 m,  
753 >100 m) based on evident biotic shifts noted at these approximate depths from the literature  
754 reviewed herein (see Burd, 2003a). An example of such a depth factor can be seen in Palsson et  
755 al. (2003), who state that in the fully surveyed Washington State side of the BC/Washington  
756 transboundary bottom trawl survey of 2001, 60% of the invertebrate biomass was found in the 5-  
757 20 fathom (approximately 10-37m) depth range. Although this depth range was not surveyed on  
758 the BC side of the SoG, invertebrate biomass declined dramatically with depth in the deeper  
759 sampling strata.

760

761 The depth ranges are defined as follows:

- 762     **A.** 0-30 m corresponds, approximately, to the euphotic zone (depths within which light  
763     penetrates), although the depth of this zone varies considerably along the BC coast in  
764     relation to exposure and water clarity. 0 m depth is considered to be mean low tide, so  
765     that habitats within this depth range are subtidal;
- 766     **B.** 30-100 m encompasses the zone which, generally, has adequate water oxygenation due to  
767     influence of wind and tidal currents and which includes subtidal organisms and no  
768     primary producers. In any one location, the consistency of benthic communities in this  
769     depth range will depend on depth-related shifts in habitat type, physical features and  
770     hydrographic processes. Many of the major taxa, however, have habitat depth ranges  
771     which span 30-100 m;
- 772     **C.** >100 m encompasses habitats which experience a progressive decline in organic input  
773     and bottom currents, leading to considerable change in the benthic communities. In near-  
774     shore areas, these depths often occur at the bottom of basins (e.g. fjords) or the foot of  
775     coastal slope areas (SoG).

776

777 Because the complete particle size distribution (including an assessment of flocculent material)  
778 provides the most thorough information about depositional history, it is recognized that the  
779 following five substrate types are simplistic (Burd 2003a). In addition, many habitats,  
780 particularly near shore, are a heterogeneous mix of different substrate types over relatively small  
781 areas. The 5 substrate types, and general features of these substrates regardless of depth, are  
782 summarized below.

783

784 1. **Mud bottoms (>95% silt/clay)** typically occur in low energy areas and are sticky

785 and tightly packed; mean sediment grain size is &lt;0.06 mm.

786 2. **Silt/Sand** substrates are a mixture of these two sediment types. The mean

787 sediment grain size for this substrate type ranges from 0.04 to 0.5 mm.

788 3. **Sand (>90% sand)** substrates are typical of areas with moderate to high bottom

789 currents and/or wave action and exposure, which prevent deposition of finer,

790 marine deposits. Sediment grain size ranges from 0.5 mm to 2 mm.

791 4. **Coarse sand, gravel or fine cobble** sediments have a grain size from 2 mm to 26

792 cm. These substrates are less mobile than the previous substrate type, due to the

793 size and weight of the particles, and are mobile only in high energy habitats.

794 5. **Rocky** substrates are composed of large cobble, boulders or bedrock and include

795 reefs and outcroppings, rocky shorelines and fjord walls.

796 The above 5 substrate types are discussed in more detail below, citing research from both the

797 SoG and similar environments elsewhere. These more detailed descriptions are relevant to

798 understanding the diversity of subtidal habitats in the SoG. These depth- and substrate-specific

799 habitats are described, including biotic structure, for the SoG using information gathered from a

800 variety of data sources including unpublished remote sampling, submersible and ROV work,

801 collections of data in unpublished data reports. Hence, these generic descriptions of the SoG

802 subtidal habitats are synthesized and, in some cases, extrapolated from a variety of sources and

803 do not lend themselves to specific citations. However, specific type examples from the SoG are

804 provided for each depth- and substrate-specific habitat, including benthic invertebrate

805 community data, when available.

806

807 **2.2.1 Mud (silt/clay) Habitats**

808

809 The finest substrate habitats in the SoG are found typically in low energy areas. Although bottom  
810 turbidity is unlikely due to storm, wave or current exposure in these low energy environments, it  
811 can be caused by physical disturbance such as bioturbation and anthropogenic mechanisms. The  
812 fine, often flocculent bottom material may take some time to settle once it is suspended via  
813 bioturbation (c.f. Orvain et al., 2003). This is likely the case at fish farms, for example, where  
814 organic ooze under the nets is sometimes resuspended by falling debris (e.g. sloughed material)  
815 from the overlying nets (Stucchi et al., 2005). However, a distinction should be made between  
816 turbidity resulting from static resuspension, due to physical disturbance in mud substrates, and  
817 turbidity due to mobile suspended solids resulting from up-stream slope failures in estuaries (c.f.  
818 Prior et al., 1987). In the first case, and for most mud sediments, typical bottom disturbances  
819 result in low net sediment transport. However, for up-slope failures or slumps, there likely will  
820 be considerable transport and bottom turbidity can persist for some time (Prior et al., 1987;  
821 Bornhold et al., 1994).

822

823 Sediment organic content can be highly variable in silt/clay sediments, depending not only on  
824 organic deposition but also on inorganic deposition (see Burd et al., in press). For example, high  
825 glacial silt deposition in more northerly mainland fjords tends to be low in organic content (c.f.  
826 Farrow et al., 1983). The ratio of organic to inorganic deposition can be related to water depth  
827 since, with increasing depth, inorganic (land-based) deposition tends to decrease while the  
828 deposited material becomes increasingly dominated by marine detritus (c.f. Rhoads and Young,

829 1970). In the southern SoG (i.e. south of Texada Island), deposition to mud substrates is  
830 dominated by particulates from the Fraser River (Thomson, 1981; Harrison et al., 1983;  
831 LeBlonde, 1983; Johannessen et al., 2003). This deposition produces organic carbon levels in  
832 surface sediments averaging around 1% near shore in the most southerly portion of the main  
833 basin and around 2% in the deeper basin sediments, closer to Texada Island (Burd et al., in  
834 press). This observed trend is due to declining riverine deposits and increasing marine  
835 deposition (Johannessen et al., 2005b). In the northern SoG, the basin sediments show unusually  
836 high %TOC (3-6%) but the overall flux of organic material, and total sediment, to the benthos is  
837 low (Johannessen et al., 2003; Burd et al., in press). Stable isotope data and biological samples  
838 also suggest that organic material in sediments in the northern SoG is not particularly labile  
839 (Burd et al., in press; Macdonald et al., in press).

840  
841 Not surprisingly, mud substrates are usually suboxic or anoxic, although %TOC varies (~1-7%)  
842 depending on the levels of inorganic input, and hydrogen sulphides or other metabolic  
843 byproducts may build up depending on redox levels and labile organic input. In shallow mud  
844 (silt/clay) substrates, sulfate reduction tends to be linked to a significant proportion (>50%) of  
845 carbon oxidation, whereas in deeper mud sediments (continental shelf) the breakdown of organic  
846 material is relatively evenly distributed between aerobic and anaerobic (sulfate reduction)  
847 processes (Kristensen and Kostka, 2005). The density of infaunal burrows, however, can have a  
848 profound dampening effect on anaerobic metabolism as a result of the increased oxygen supply  
849 to subsurface sediment layers. The predominant type of burrowing is related to trophic mode  
850 (Nickel and Atkinson, 1995), as well as sediment texture and geochemistry. Fine sediments tend

851 to be dominated by surface deposit feeders or above-surface filter feeders (Kristensen and  
852 Kostka, 2005), rather than sub-surface deposit feeders.

853

854 Extensive surface bioturbation without the binding influence of intact burrows can destabilize  
855 fine surface sediments by producing a surface (“fluff”) layer which is readily re-suspended (c.f.  
856 Rhoads and Young, 1970; Orvain et al., 2003). Rhoads and Young (1970) even suggest that  
857 surface fluff layers tend to prevent suspension feeding due to the clogging of feeding apparatus  
858 and the inhibition of larval settlement. The authors use this suggestion to explain the distinct  
859 dichotomy in dominant feeding types: deposit-feeders in soft, fine sediments versus suspension  
860 feeders in sandier, or firmer, mud sediments. Following this line of reasoning, an assessment of  
861 the feeding guilds in sediments could provide some insight into the sediment texture and  
862 porosity, as well as near-bottom turbidity.

863

864 The fine-grained particles of mud substrates tend to contain considerable organic particulate  
865 material in various forms, thereby providing a good substrate for bacterial and/or algal  
866 production (Kristensen, 1988). Key general biotic features of mud bottoms include extensive  
867 bacterial or algal mats or shallower near-surface invertebrate burrows that provide sediment  
868 surface cohesion in shallow depths, or from invertebrate burrows. Microbial activity, which  
869 breaks down organic material in marine sediments (Kristensen and Kostka, 2005), can be  
870 stimulated by the presence of surface mucous layers from meiofauna (see Probert, 1984). The  
871 stimulation of both microbial and meiofaunal activity creates a rich organic food layer for  
872 macrofaunal deposit feeders (Hoskins et al., 2003, Hannides et al., 2005; for review see  
873 Kristensen and Kostka, 2005). In addition, mucous layers from intertidal mudflat diatoms,

874 bacteria and mucous-lined burrows can also help to bind the sediment surface (c.f. Decho, 2000;  
875 de Brouwer et al., 2005). Mucous burrows are often impermeable to dissolved organic material  
876 and redox chemicals in order to protect the animal from harsh chemical environments (c.f.  
877 Hannides et al., 2005; Kristensen and Kostka, 2005). However, depending on their structure,  
878 these burrows do provide a pathway for exchange of overlying water with deeper sediments, thus  
879 preventing the buildup of potentially inhibitory metabolic byproducts (see Zorn et al., 2006).  
880 However, the importance of both bacterial and diatomaceous mucous layers in sediments  
881 declines in importance with increasing depth from the intertidal zone to the bottom of the  
882 euphotic zone (Ziervogel and Forster, 2006).

883

884 Where oxic sediments are present in these habitats, macrofauna are primarily deposit feeding  
885 shallow burrowers, such as polychaetes and bivalves, and predators such as various flatfish and  
886 crabs from surrounding rocky areas. Megafauna typically include a variety of echinoderms such  
887 as mud stars and burrowing holothurians.

888

#### 889 **2.2.1.1 Shallow (0-30 m) mud**

890 Mud substrates in the shallow subtidal tend to be protected from wave exposure and typically  
891 have low tidal currents. Bottom turbidity in these habitats is likely due to physical disruption  
892 from erosional events, delta slope failures or other unusual events. These habitats typically  
893 occur in low flow estuaries and at the base of low current rocky outcrops. Shallow mud habitats  
894 can be found in quiescent bays surrounded by rocky headlands, and in wave and current  
895 protected estuaries with either low freshwater flow or where there is heavy glacial silt in runoff  
896 (i.e. estuaries of mainland fjords; see Farrow et al., 1983).



897

898 These are typically highly productive areas because they are within the euphotic zone, which  
899 allows primary production as well as bacterial production on and within the sediments. They are  
900 also common in coastal areas with physical developments that block or break up wave erosion  
901 (e.g. marinas, breakwaters, etc.). Surface shell debris can be common, attesting to the  
902 importance of bivalves in this food chain. Organic carbon flux to the sediments may be high  
903 and, hence, sediment %TOC may also be high depending on the level of inorganic input. (Boyd  
904 et al., 1998). If the input is primarily salt-marsh plant debris, however, the organic material may  
905 have low lability. Primary production in these habitats is primarily from benthic micro-algae and  
906 blue-green algae (refs). These sediments typically have a high level of bacteria, which can  
907 include sulphur-fixing species (refs).

908

909 Usually, these areas have oxygenated bottom water, with sufficient oxygen for shallow  
910 burrowers that are mostly deposit feeders (bivalves and polychaetes), epifauna (scavenging  
911 amphipods and bottom shrimp), surface grazers (gastropods) and predators (mud stars, brittle  
912 stars, heart urchins, echinurans, drills, fish) (Burd, 1992). In some habitats, mud-dwelling sea  
913 cucumbers such as *Molpadia* or *Chirodota* may be found if there is sufficient oxygen in surface  
914 sediments (Burd, 1992). Meiofauna, particularly nematodes, are important in these shallow  
915 subtidal mud habitats (see section 1.1).

916

917 Examples can be seen in areas such as Patricia Bay, Saanich Inlet, and around numerous  
918 estuarine bays in the Strait. Unfortunately, there are few published examples of shallow subtidal  
919 mud studies in the SoG. Burd (1992) and Boyd et al. (1998) described mud assemblages from

920 shallow areas of the innermost part of Burrard Inlet (Port Moody Arm). These substrates had  
921 low invertebrate abundance and biomass compared with deeper, coarser substrate areas further  
922 out in the inlet, and were dominated by polychaetes, followed by bivalves and crustaceans.  
923 Faunal composition was distinct between Port Moody Arm and areas further out in the inlet  
924 (Burd, 1992) and in some areas with reducing sediments, dominated by the tolerant opportunistic  
925 polychaete *Capitella capitata* complex (Boyd et al., 1998). Considerable sediment chemical  
926 contamination and organic enrichment are evident in the Port Moody Arm area (see Burd, 1992;  
927 Boyd et al., 1998).

928

#### 929 **2.2.1.2 Mid-depth (30-100 m) mud**

930 Mud substrates at 30-100 m depth are a common marginal habitat around the SoG, particularly  
931 on the eastern side, including Burrard Inlet, north along the coast, and in isolated bays with low  
932 bottom currents (Fig. 1). These fine-grained substrates are not found in areas exposed to sandy  
933 deposition from the southern Gulf Islands, the Fraser River discharge and other relatively large  
934 freshwater estuaries such as the Cowichan River (north of Saanich Inlet), and the Squamish  
935 River (Howe Sound). This type of habitat is commonly found inside the sill, or near the mouth of  
936 fjords, in areas with either limited, or absent, bottom currents and very low freshwater runoff.  
937 These habitats may also occur surrounded by, or at the base of, rocky outcrops or cliffs. Bernard  
938 (1978) lists the dominant invertebrate epibenthic megafauna (11 species) found in mud/silt  
939 habitats from 20-100 m depth at multiple locations within the SoG.

940

941 Because of the depth range, these habitats tend to have limited tidal influence and no wave  
942 influence. In addition, as the mud substrates are below the euphotic zone, the development of

943 surface biofilms may be less extensive than in shallow subtidal mud habitats (c.f. Ziervogel and  
944 Forster, 2006). If the redox boundary occurs at the sediment surface, however, sulfide-fixing  
945 bacteria such as *Beggiatoa* spp. may produce mucous mats. For example, *Beggiatoa* spp. mats  
946 can be found between 65-100m depth in areas of Saanich Inlet (Burd, unpublished data; see >100  
947 m anoxic basins, below).

948  
949 An example of this type of habitat is bottom areas shallower than sill depth in Saanich Inlet, such  
950 as Patricia Bay (<http://www.env.gov.bc.ca/wat/wq/saanich/siscr.html>). Although there have been  
951 no studies focused on the benthic soft-bottom fauna in the mid-depth range of Saanich Inlet  
952 sediments, another example of this habitat type in the SoG, for which data are available, is outer  
953 Burrard Inlet. Sedimentation rates are low in this region (Johannessen et al., in press), although  
954 the complex hydrographic mixing results in high suspended particulates in the water column (as  
955 noted during reconnaissance ROV surveys – CORI, 2002) and sediment TOC levels between 1.5  
956 and 2% (McPherson et al., 2006b). Although there are a variety of anthropogenic discharges and  
957 physical disturbances in the inlet (see Section 3), long-term monitoring for the outer inlet  
958 suggests that benthic infauna are not impoverished and are not dominated by opportunistic  
959 polychaetes (c.f. PICES, 2001; McPherson et al., 2006b). Fauna within the inlet are dominated  
960 by small burrowing bivalves, which constitute ~55-85% of the total abundance over a range of  
961 sediment enrichment conditions and which contribute the largest percentage of biomass of any  
962 major taxonomic group (McPherson et al., 2006b). Polychaetes constitute 10-40% of the total  
963 abundance and species numbers are within the ranges expected for this depth range in the SoG  
964 (Burd et al, in press). Ophiuroids are patchily abundant and both crustaceans and holothurians  
965 are rare in this inlet.

966

967 Data are also available for shoreline areas just outside the north side of Burrard Inlet which fit  
968 this habitat type (McPherson et al., 2004a). Biotic samples taken from a similar depth to the  
969 outermost Burrard Inlet show similar species richness to the Burrard Inlet samples but somewhat  
970 lower abundance levels (McPherson et al., 2004 a, c). Fauna increase in abundance from outside  
971 the inlet to the innermost part of the outer basin (west of 1<sup>st</sup> Narrows) (Fig. 1), with bivalves  
972 showing the clearest abundance gradient (McPherson et al. 2004 a,c). Like Burrard Inlet, the area  
973 just outside the north side of the inlet experiences relatively low sedimentation rates compared to  
974 the rest of the southern SoG, as well as moderate %TOC in the sediments (~1.5%) Burd et al., in  
975 press; (Johannessen et al., in press).

976

977 Biotic and synoptic sediment geochemical and contaminant sampling data have been collected  
978 for parts of inner Burrard Inlet (past 1<sup>st</sup> Narrows), including the two inner arms (see Fig. 1) (Burd  
979 and Brinkhurst, 1990; Cross and Brinkhurst, 1991; Boyd et al. 1998; PICES, 2001; Je et al.,  
980 2003). In addition, samples from the outer inlet were collected by Ellis (1971). These studies  
981 suggest that faunal abundance and species richness decline along a gradient from 1<sup>st</sup> Narrows  
982 inward towards Port Moody Arm (Fig.1), where the heaviest organic enrichment and  
983 contamination is found. In Port Moody Arm, which has fine mud sediments with poor flushing,  
984 faunal abundance tended to be temporally variable relative to the rest of Burrard Inlet (Burd  
985 1992; Boyd et al., 1998) but faunal biomass was consistently lower.

986

987 The spectrum of studies utilizing the same locations in Burrard Inlet but using different mesh  
988 sizes (0.3, 0.5 mm and 1 mm) for screening biotic samples, provides a unique opportunity to

989 examine the difference in interpretation which is potentially possible for community structure  
990 based on methodology. Ignoring potential differences in quality control of sampling, increasing  
991 screen mesh size led to a decreasing proportion of juvenile (non-adult) forms at one outer  
992 harbour station (~ 50% to 10%) but no notable shift in species number. However, the proportion  
993 of abundance made up of bivalves shifted from ~35% to 55%, with a commensurate decrease in  
994 proportion of polychaetes. In addition, although usually ignored in benthic macro-infaunal  
995 studies, the proportion of nematodes collected decreases with increasing mesh size. Hence, the  
996 1mm screen appears to eliminate most of the juvenile fauna, as well as a modest proportion of  
997 the smaller adult polychaetes and most of the “meiofauna” (primarily nematodes and  
998 harpacticoid copepods). The most dramatic change in metazoan size spectra, biota types and life  
999 history strategies appears to be found at about the 0.5 mm screen size, and the evolutionary  
1000 drivers for the meiofaunal/macrofaunal dichotomy are discussed by Warwick et al. (2006). The  
1001 various studies agree that polychaete dominance increased from the outer inlet towards the more  
1002 eutrophic Port Moody Arm (Boyd et al., 1998; Burd and Brinkhurst, 1990; Je et al., 2003), with  
1003 some examples of opportunistic enrichment of *Capitella capitata* complex (Burd and Brinkhurst,  
1004 1990; Je et al., 2003).

1005

### 1006 **2.2.1.3 Deep (>100 m) mud**

1007 Deep water mud habitats are not subject to tidal or wave influences, usually have very low  
1008 bottom currents and limited flushing of bottom water. The origin of organic material in these  
1009 environments is primarily marine detritus or terrestrial erosion from cliffs in fjords. Bottom  
1010 turbidity can occur as a result of turbidity flows from delta slope failures in fjords (Prior et al.,  
1011 1987; Bornhold et al., 1994). In general, substrates get finer with increasing depth in coastal

1012 areas (Striplin, 1996; Llansó et al., 1998) because the input of coarser land-based erosional,  
1013 riverine and current-transported material tends to decline with increasing depth. Organic carbon  
1014 flux to these deep sediments is typically, although not always (Burd et al., in press), lower than  
1015 in similar sediments in shallower areas, unless there is a specific source of organic input nearby  
1016 (e.g. fish farms).

1017  
1018 Areas with oxygenated, mud sediments are extensive throughout both the deep basin of the SoG  
1019 and many of the fjords, and probably make up most of the subtidal bottom area of the SoG  
1020 (Levings et al., 1983). Bottom water oxygen levels vary, depending on basin topography, but low  
1021 bottom currents and shallow, isolating sills in fjords can result in significantly reduced bottom  
1022 oxygen levels. Hence, there is limited oxygen replenishment to the sediments. These habitats  
1023 are typical of the main basins of fjords and the deep basin of SoG. These sediments are  
1024 dominated by near-surface, or epifaunal, deposit feeders and predators. Bivalves and ophiuroids  
1025 are less abundant in these deep habitats than in shallower areas, while polychaetes, holothurians  
1026 and echinoids increase in dominance (see Burd et al., in press). Bernard (1978) provides a list of  
1027 the dominant (largely epibenthic) megafauna collected in trawl samples at locations throughout  
1028 the SoG at depth ranges of 100-200 m, 200-300 m, and 300-400 m. Bernard's (1978) species list  
1029 is the most diverse in all depth ranges for this substrate type, and includes bivalves, polychaetes,  
1030 echinoderms and crustaceans.

1031  
1032 Because organic carbon flux is low, faunal abundance and species richness is generally lower  
1033 than in the mid-depth marginal SoG mud habitats discussed earlier. Llansó et al. (1998) describe  
1034 biotic conditions in deep clay habitats >80 m in Puget Sound. They suggest that, on average,

1035 species richness and abundance was lowest in deep (>80 m) clay sediments of any soft substrate  
1036 types in the sound or on the Washington shelf. Llansó et al. (1998), Burd and Brinkhurst (1992)  
1037 and Burd (2003b) agree that several of the large, important bioturbators (the echinoderms  
1038 *Molpadia intermedia* and *Brisaster latifrons*) seem to be primarily found in deep-water  
1039 sediments, which in the fjords and main basin of the SoG are typically mud (silt/clay).

1040

1041 Some data on the benthic infaunal biota, collected using visual and remote sampling methods,  
1042 are available for the fjords (Burd and Brinkhurst, 1992; Ellis, 1971; Levings, 1980a, b). Burd and  
1043 Brinkhurst (1992) report infaunal abundances in silt sediments at depths of >100 m in of three of  
1044 the SoG fjords: Bute, Toba and Jervis. Faunal abundance was low at all sampling stations in that  
1045 study and was dominated by polychaetes; occasional high abundances of sipunculids were  
1046 recorded but few echinoderms and virtually no crustaceans or bivalves were observed (Burd and  
1047 Brinkhurst, 1992). Burd (1992) did a multivariate comparative assessment of biotic assemblages  
1048 from a series of deep fjord samples along BC's mainland coast compared with other assemblages  
1049 found throughout BC. One notable feature of BC's deep fjords is the relative uniformity of  
1050 benthic assemblages in the deep mud benthos, compared to other coastal areas, in the absence of  
1051 overwhelming physical drivers such as anoxia or hypoxia, heavy glacial deposition or freshwater  
1052 runoff (c.f. Burd 1992).

1053

1054 Ellis (1971) described fauna from some grab samples taken in the deepest basin of Jervis Inlet on  
1055 the mainland BC coast. They note that about 80% of biomass from that area was contributed by  
1056 the echinoderm *Brisaster latifrons* and a surface tube-mat forming polychaete; approximately  
1057 10% of the total biomass was contributed by bivalves.

1058  
1059 A deep mud-bottom habitat in Knight Inlet (located immediately north of the SoG), described in  
1060 Farrow et al. (1983), is a good example of a fjord with high loads of river-borne glacial silt.  
1061 These loads of glacial silt add to the inorganic loading near the head of the inlet, while also  
1062 introducing sufficient energy and flocculent material into the system to produce high turbidity  
1063 and bottom resuspension or turbidity flows. This turbulent type of habitat is unsuitable for many  
1064 soft-bottom species which may suffer from smothering (e.g. Holte and Gulliksen, 1998;  
1065 Wlodarska-Kowalczyk et al., 2005). In Knight Inlet, BC, Farrow et al. (1983) found a down-inlet  
1066 gradient of increasing diversity of large suspension-feeding organisms, and a change in epifauna  
1067 from mobile shrimp and crabs at the turbid, high inorganic input head of the inlet, to burrowing  
1068 shrimp in the middle inlet, to ophiuroids in the least turbid and least inorganic input areas of the  
1069 lower inlet. Similar trends have been observed elsewhere; for example Wlodarska-Kowalczyk et  
1070 al. (2005) describe the spatial gradient in sediment biota away from heavy glacial silt  
1071 sedimentation towards the head of a European fjord as showing similar trends in faunal  
1072 abundance and species richness as those found in organic enrichment gradients. Changes in  
1073 species diversity and types of sponges related to water turbulence and sedimentation in an Irish  
1074 sea lough were also noted by Bell and Barnes (2000a, b).

1075  
1076 During the SoG Ambient Monitoring Program (Wright et al., in press), deep-water mud habitats  
1077 were sampled at two stations. One station was within the deepest part of the SoG basin (388 m),  
1078 just south of Texada Island (Fig. 1), and had moderate organic flux to sediments while the  
1079 second station was north of the mid-basin sill near Texada Island (187 m) and was within the low  
1080 organic flux regime in the northern SoG (see Burd et al., in press). In addition, the organic



1081 carbon at the shallower, more northern station was relatively refractory compared with the  
1082 deeper, southerly station, and had a high clay component, with virtually no terrigenous or shell  
1083 debris. The difference in these substrate conditions produced a striking difference in biota, which  
1084 was much more abundant and diverse at the deeper, southerly station. However, similarities  
1085 between the two stations include polychaete dominance, the lack of bivalves and crustaceans,  
1086 and the presence of large burrowing holothurians. In fact, this latter group was responsible for  
1087 the relatively high faunal biomass at the deeper, southerly station (Burd et al., in press).

1088

1089 Saanich Inlet, below sill depth (70 m) (Fig. 1), is an example of a deep anoxic basin. It  
1090 experiences progressive hypoxia and anoxia from winter through summer. In the fall, upwelling  
1091 within the SoG spills dense, oxygenated water over the sill and, sinking to the bottom, this water  
1092 pushes the anoxic layer up to mid-water depths before the anoxic waters disperse  
1093 ([http://www.pac.dfo-mpo.gc.ca/sci/OSAP/projects/bcinlets/saanich\\_inlet\\_e.htm](http://www.pac.dfo-mpo.gc.ca/sci/OSAP/projects/bcinlets/saanich_inlet_e.htm)). Saanich Inlet  
1094 has high organic carbon content in deep sediments (Bornhold, 1978) but a moderate C/N ratio  
1095 (~6.8), suggesting that, historically, the origin of organic input has been largely marine. The high  
1096 carbon content in Saanich Inlet deep sediments has been supported by more recent studies  
1097 (Boatman and Murray, 1982; Tunnicliffe, 2000), however Tunnicliffe (2000) indicates that  
1098 increasing terrestrial input over the past century has resulted in shifts in organic carbon content,  
1099 and therefore, the C/N ratio. Organic carbon may build up in sediments because overlying water  
1100 hypoxia and anoxia greatly slow the decomposition and consumption of this material by bacteria  
1101 and invertebrates, respectively (Emerson and Hedges, 2003). Although the cliff fauna of  
1102 Saanich Inlet have been studied, (Tunnicliffe, 1981; Burd and Brinkhurst, 1984), information on  
1103 the infaunal benthos of the deep mud basin is lacking. However, because of the occasionally

1104 vertically mobile anoxic water layer in this inlet, along with observed mass mortalities of cliff  
1105 fauna (Tunncliffe, 1981; Burd and Brinkhurst, 1984), it has been assumed that soft-bottom areas  
1106 influenced by long-term anoxia will be largely azoic.

1107

1108 At the sediment interface, where dissolved oxygen is minimal and sediments are anoxic, white  
1109 mucous mats of *Beggiatoa* spp. and similar sulphur-fixing bacteria may form (Burd and  
1110 Brinkhurst, 1984). In this oxycline, the sediments are devoid of any sign of bioturbation or  
1111 evidence of infaunal or epifaunal life (Gucluer and Gross, 1964; Burd, unpublished data; PICES  
1112 IV observations 1980-1983), with the following exceptions. A benthic-pelagic amphipod species  
1113 (*Orchomene obtusus*) can tolerate anoxic conditions for extended periods of detrital scavenging,  
1114 after which they migrate back up to oxygenated water periodically (De Robertis et al., 2001).  
1115 The galatheid crab, *Munida quadrispina*, has been observed to frequent silty bottom areas where  
1116 the mucous mats are present and near-bottom water oxygen levels are very low (Burd and  
1117 Brinkhurst, 1984) and has been observed, *in situ* and in the laboratory, to feed opportunistically  
1118 on sediment detritus and the aforementioned amphipods. The crabs have exceptional metabolic  
1119 regulation under low oxygen conditions in the laboratory (Burd, 1985), along with significantly  
1120 hypertrophied gill tissue in the deep areas of Saanich Inlet (Burd, 1988), compared with  
1121 surrounding areas outside the inlet. In the deep, severely hypoxic to anoxic sediment areas, these  
1122 are the only visually evident fauna although facultative anaerobic meiofauna (typically  
1123 nematodes) may be present in sediments.

1124

1125 Like Saanich Inlet, Howe Sound on the mainland coast of BC has a shallow sill at the entrance  
1126 and experiences hypoxic conditions in the deep basin for part of the year. Historical bottom

1127 trawl surveys in Howe Sound related to bottom hypoxia are described in Levings (1980a, b) and  
1128 Levings et al. (1983). Survey data show that the relatively immobile invertebrates and a few  
1129 slow-moving fish experienced mass mortalities during severe hypoxic periods; bottom fish  
1130 catches declined, presumably due to migration to shallower, more oxic waters. The mobile  
1131 epifauna appeared to return fairly rapidly following hypoxic periods, including the galatheid  
1132 crabs also found in Saanich Inlet, and various shrimp species (Levings 1980a, b).

1133

### 1134 **2.2.2 Silt/Sand Habitats**

1135

1136 The presence of sand implies transport of inorganic material, from nearby glacial deposits or  
1137 moderate to high input from freshwater sources nearby. Although variable spatially and  
1138 temporally, these sediments are net depositional. In coastal areas with a source of relatively  
1139 coarse, inorganic material from large riverine inputs, the sediments tend to be mixed. This type  
1140 of habitat is common in marginal coastal areas in the southern SoG, particularly along the eastern  
1141 margin of the southern Strait where the Fraser River discharges. For a description of  
1142 sedimentary dynamics along the Fraser River delta, see Hill et al. (in press). Most notable about  
1143 these sediments is the input of coarse material that increases mobility beyond that found in mud  
1144 substrates. The delta sediments along the bank and slope where the Fraser River discharges into  
1145 the SoG provide a good example of this mobility, as the sediments appear to be continuously  
1146 transported to the north and downslope (McLaren and Ren, 1995; Hodgins and Hodgins, 2000).  
1147 The importance of sediment mobility in determining the distribution and stability of coastal  
1148 benthic infauna has been documented in Australia (Post et al., 2006), New Zealand (Hewitt et al.,  
1149 1997; for a general review see Newell et al., 1998), and in laboratory experiments (Roegner et

1150 al., 1995; Dunn et al., 1999; Hunt and Mullineaux, 2002). Research in the northeast Pacific has  
1151 focused on transport of sediment particle sized organisms such as foraminifera (Snyder et al.,  
1152 1990).

1153

1154 In the sediments influenced by Fraser River deposits, the relatively high deposition of inorganic  
1155 riverine material seems to limit the TOC levels to values  $<1.5\%$  (McPherson et al., 2006a; Burd  
1156 et al., in press). However, these TOC values are not indicative of the productivity of these  
1157 sediments, which is more closely related to the input of organic material (see Burd et al., in  
1158 press). Because of the inorganic input to these sediments, however, and their tendency to be less  
1159 sticky and cohesive than mud, they are usually better oxygenated than marine muds. Surface  
1160 mixing layer depths related to bioturbation in substrates affected by Fraser River discharge are  
1161 estimated at between 7-10 cm deep (Johannessen et al., in press). These substrates tend to be  
1162 located in moderate or variable current regimes and, because the sediments are easily re-  
1163 mobilized, bottom turbidity may occur. These substrates are typically oxic but, if organic carbon  
1164 loading is high, can be suboxic.

1165

1166 A wide range of habitat types, based on fine-scale structural features, can be found in these  
1167 substrates, along with a mixture of biotic features of both mud and sand communities. Analyses  
1168 of biotic data with an extensive geographic distribution within the SoG (Burd et al., in press),  
1169 indicates that this silt/sand habitat along the Fraser River delta appears to have a high abundance  
1170 of invertebrate fauna compared with the rest of the SoG. Biota are diverse in terms of species  
1171 richness, type (polychaetes, bivalves, echinoderms, crustaceans and more) and size spectrum of  
1172 organisms, as well as feeding types (mixed deposit and/or suspension feeders, scavengers and

1173 predators) (McPherson et al., 2006a). Using functional group categories for benthic fauna,  
1174 Pearson and Rosenberg (1978) suggest that off-shore silt/sand habitats in temperate coastal areas  
1175 tend to have the greatest diversity of functional groups in soft sediments.

1176

#### 1177 **2.2.2.1 Shallow (0-30 m) silt/sand**

1178 Shallow silt/sand habitats in the SoG are usually semi- protected in regard to wave exposure and  
1179 tidal currents. Sediment is either fluvial in origin or from an along-shore source. Oxygen levels  
1180 in bottom water are reasonable and natural sediments tend to have some oxygenation. In the  
1181 SoG, eelgrass occurs in oxic sediments in areas with “clean” water and at depths usually <10 m.  
1182 Both red and green macroalgae are associated with eelgrass beds, as a result of the low sediment  
1183 mobility (eelgrass roots/rhizomes stabilize the sediments). In the shallow silt/sand habitats in the  
1184 SoG, mobile macrofauna (e.g. sea stars and crabs) are abundant and, usually outside of the  
1185 eelgrass beds, deep-burrowing large bivalves as well as burrowing anemones, agglutinated tube-  
1186 building worms and tubicolous amphipods occur.

1187

1188 Bazan Bay on Vancouver Island, serves as an example of some of the more interesting features  
1189 that may occur in these shallow silt/sand habitats. A mixed eelgrass, red and green filamentous  
1190 algal community is evident to the 10 m depth (J. Harper, CORI, Sidney, BC, pers. comm.), along  
1191 with patches of eelgrass that vary in density (see Bornhold and Harper, 2002). Eelgrass beds are  
1192 typically considered to be important habitat and nursery areas for various species of fish and  
1193 mobile, or epiphytic, macro-invertebrates (Goldstein et al., 1996; Heck et al., 2003;  
1194 <http://www.ecy.wa.gov/programs/sea/pugetsound/species/eelgrass.html>)

1195

1196 In deeper waters, but still within this habitat type, foliose red algae and other macroalgae are  
1197 seasonally abundant, suggesting attachment in the relatively stable silt/sand substrates. Benthic  
1198 invertebrate data from close proximity to an abandoned outfall pipe in Bazan Bay was collected  
1199 (Glaholt et al., 2002) as part of the reconnaissance information related to the proposed SoG  
1200 Crossing pipeline project. The study was designed to show the expected changes in biota related  
1201 to the introduction of an artificial reef (a pipeline), into a shallow, silty sand habitat in the SoG.  
1202 The faunal assemblage in these substrates is dominated, to an indeterminate water depth, by a  
1203 dense sediment-surface mat of tube-dwelling amphipods, sponges and hydroids, with lesser  
1204 dominance by polychaetes, followed by bivalves (Glaholt et al., 2002). The presence of these  
1205 mats suggests a lack of bottom disturbance from excessive sedimentation, organic input or  
1206 physical disruption. The presence of sponges and hydroids in the mats suggests a strong  
1207 suspension feeding component within the community. The amphipod tubes produce a micro-  
1208 heterogeneity of structure which benefits other species, such as the hydrozoans and a multitude  
1209 of other amphipods and crustaceans. Faunal distributions were highly variable spatially, with  
1210 isolated patches of anoxic sediments and higher silt content where drift algae had piled up on the  
1211 quiescent down-current side of the Bazan Bay pipeline (Glaholt et al., 2002). Other infaunal  
1212 organisms which may be common in shallow silt/fine sand habitats include relatively deep  
1213 burrowing, large bivalves, burrowing anemones, and larger mobile predators and scavengers  
1214 (e.g. mud stars, crabs, shrimp and nudibranchs).

1215

1216 Another example of a shallow mixed silt/sand habitat study is Boatswain Bank along the eastern  
1217 coast of Vancouver Island just north of Saanich Inlet. A shallow subtidal study was done along  
1218 an onshore/offshore transect at the proposed landfall for the SoG pipeline. The relevant habitat,

1219 macroalgae and surface megafauna are described based on diver surveys in Seacology et al.  
1220 (2001). Megafauna included sea-pens, tubeworms, gastropods, hermit crabs, sand stars, and  
1221 various fish. Beach seining in the same study showed a number of rock, kelp and helmet crabs.  
1222 Concurrently, a study of the infauna (Burd and Glaholt, 2000) showed a diversity of polychaete,  
1223 bivalve, crustacean and echinoderm fauna with numerous bryozoan and cnidarian colonies  
1224 attached to fauna and macroalgae. The diversity of this assemblage appeared to be comparable to  
1225 the deeper, siltier samples in Satellite Channel (Burd et al. 2000a), except for a much lower  
1226 abundance of shallow burrowing bivalves in the Boatswain Bank area. The area was also  
1227 surveyed by video to map the habitat, extent of eel-grass beds and other macro-algae  
1228 (Archipelago Marine Research Ltd., 2000).

1229

#### 1230 **2.2.2.2 Mid-depth (30-100 m) silt/sand**

1231 Mid-depth silt/sand habitats in the SoG tend to have a broad range of organic carbon fluxes and  
1232 bottom water oxygen levels. An example of the mid-depth silt/ sand habitat is found on the  
1233 western side of the SoG, straddling the Fraser River discharges. Extensive biological and  
1234 geochemical monitoring of these sediments has been conducted as part of the Iona outfall  
1235 monitoring program for GVRD (Burd, 2000; Burd, 2003b; Bailey et al., 2003, McPherson et al.,  
1236 2003, 2004b, 2005a, 2006a, 2007a), providing extensive data on both background and impacted  
1237 areas (see Section 3). This area spans the Fraser River delta and hence receives the maximum  
1238 influence from plume particles and bottom transported material, particularly from the south arm  
1239 of the Fraser River (Hill et al., in press). Bioturbation in the area is considerable, with a surface  
1240 mixed layer of up to 5-10 cm (Johannessen et al., in press). The area has a rich and diverse  
1241 macrofaunal community dominated by a broad size range of bivalves, although 40- 60% of the

1242 total faunal abundance is contributed by one small, burrowing species, *Axinopsida serricata*. A  
1243 second bivalve, *Macoma carlottensis*, comprises ~10% of the abundance. All bivalves comprise  
1244 ~50% of the organismal biomass in these sediments (McPherson et al. 2006a). The remaining  
1245 biomass is mostly comprised of echinoderms, primarily the brittlestar *Amphiodia*  
1246 *urtica/periercta* complex, and a few large holothurians (*Molpadia intermedia*). Although there is  
1247 a diversity of polychaete taxa present, these organisms are clearly of minor importance in the  
1248 productivity of these sediments. Infaunal crustaceans are rare, comprising less than 1% of faunal  
1249 abundance and far less than 1% of biomass (McPherson et al., 2007a).

1250

1251 The bivalve dominance evident in the 30-100m silt/sand sediments spanning the Fraser River  
1252 delta, discussed above, appears to be unusual within the SoG (Burd et al., in press). Burd et al.  
1253 (op. cit.) suggest that the bivalve dominance is related to the high sedimentation rates along the  
1254 delta (see Johannessen et al., in press), which are less easily tolerated by infaunal polychaetes  
1255 (Reid and Baumann, 1985; Burd, 2002). Brittle stars may also have an advantage in this habitat  
1256 type in regard to the speed and extent of their burrowing capability. Close to the south arm  
1257 discharge of the Fraser River, the sedimentation rates are too high to be measured in the standard  
1258 box cores used in other locations (Johannessen et al., in press). In this location, the dominant  
1259 bivalve (*Axinopsida serricata*) and the ophiuroids periodically decline, with a concurrent  
1260 increase in abundance of small polychaetes typically considered to be primary colonizers  
1261 (McPherson et al., 2006a). Presumably, there is therefore a limit in the ability of the infaunal  
1262 bivalves and brittle stars to cope with heavy sedimentation conditions (or events).

1263



1264 Although mid-depth (30-100 m) sampling stations in outer Burrard Inlet are described as having  
1265 mud substrate (see earlier), several stations in this area have silt/sand substrates (i.e. stations  
1266 close to the 1<sup>st</sup> Narrows bridge and near the mouth on the south side of the inlet (Fig. 1)  
1267 Conversely, some areas along the bank and slope between the south arm of the Fraser River and  
1268 the opening to Burrard Inlet can be classified as primarily mud. Species richness values and  
1269 faunal types are similar throughout the Fraser River delta and Burrard Inlet (McPherson et al.,  
1270 2006 a, b), illustrating the overlap in faunal types between mud and sandy silt habitats. However,  
1271 regardless of substrate type, species abundance and biomass values have been consistently lower  
1272 in outer Burrard Inlet than along the Fraser River delta (McPherson et al., 2006 a, b), and total  
1273 sediment flux and organic flux are higher along the river delta than in Burrard Inlet (Burd et al.,  
1274 in press; Johannessen et al., in press). These patterns suggest that faunal productivity in the main  
1275 basin of the SoG is more dependent on the Fraser River discharge than on substrate type or depth  
1276 (Burd et al., in press).

1277

### 1278 **2.2.2.3 Deep (>100 m) silt/sand**

1279 Silt/sand habitats are rare below 100 m depth in the SoG, since most of the sand (coarser, land-  
1280 based material) deposits closer to shore. In most of the deeper parts of the main basin of the  
1281 SoG, and at the bottom of fjords, substrates are mud (see earlier text). In the southernmost part  
1282 of the main basin of the SoG, however, intense mixing throughout the water column in Haro  
1283 Strait (Masson and Cummings, 2004) (see Fig. 1) may carry sandy material eroded from the  
1284 southern gulf islands to the deep basin of the SoG (see also Johannessen et al., 2006), explaining  
1285 why these sediments have some sand content. In addition, some of the coarse, sandy sedimenting  
1286 material from the Fraser River is transported northward and downslope off the delta, ultimately

1287 ending up in the deep basin of the eastern margin of the southern SoG and resulting in mixed  
1288 sand and silt substrates at depths greater than 100 m (McPherson et al., 2004a).

1289

1290 The example used to provide a description of the biota in these habitats is the area at the foot of  
1291 the slope (120 m) on the south-eastern margin of the SoG, along the Fraser River discharge area.

1292 The biotic community of this area overlaps with that for the mid-depth range to some extent, but  
1293 there are marked differences in faunal dominance (McPherson et al., 2004a). For example, the

1294 mid-depth bivalves, such as *Axinopsida serricata*, which are dominant from 30-100 m in the

1295 Fraser River delta and outer Burrard Inlet, decline in abundance at depths >100 m in these same

1296 areas (McPherson et al., 2004a, b, c). Brittle stars are also rare below 100 m, whereas large

1297 holothuroids such as *Molpadia* increase in abundance and the crustacean fauna changes.

1298 Number of taxa and total abundance tend to decline somewhat with increasing depth but are still

1299 relatively high at 120 m. At a location close to the south arm of the Fraser River discharge (Fig.

1300 1) the main features of the fauna tend to be similar at depths from 60-120 m, because this entire

1301 habitat is overwhelmed by continuous high deposition of river-derived material. At 500 m north

1302 of the Iona outfall (McPherson et al., 2004b) (Fig. 1), and another location just outside the mouth

1303 of Burrard Inlet (McPherson et al., 2004a), faunal abundance and diversity decline dramatically

1304 with depth. Near the outfall, the faunal decline may be related to slumping of elevated (outfall-

1305 related) deposits along the steep slope areas. However, in both the aforementioned more

1306 northerly locations, faunal declines may be related to a combination of decreased sediment

1307 organic flux with depth and natural declines in bivalve abundance below 100 m (Burd et al., in

1308 press).

1309

1310 Several stations sampled in the deep, southern basin of the SoG as part of a collaborative  
1311 ambient monitoring program between the Canadian Department of Fisheries and Oceans,,  
1312 Natural Resources Canada and the Greater Vancouver Regional District (Wright et al., in press)  
1313 showed infaunal biomass as high, or higher, than that observed in the mid-depth zone along the  
1314 Fraser River delta (see earlier text this section; Burd et al., in press). Faunal abundance and  
1315 species richness were also considerably higher than those found in either of the deep, mud  
1316 habitats in fjords or other deep areas of the BC coast (Burd, 1992; Burd, 2006; Burd et al., in  
1317 press). At one southern SoG station, sediments had unusually high organic and inorganic flux,  
1318 biomass and species richness (see Burd et al., in press) and were dominated (e.g. ~40% of total  
1319 abundance) by crustaceans, particularly a cumacean (*Eudorellopsis integra*) and an ostracod  
1320 (*Eudorella pacifica*); both these crustacean species were rare in the proximate mid-depth zones  
1321 for this substrate type (McPherson et al., 2007a). Approximately 25% of the total faunal  
1322 abundance at the same station consisted of bivalves, which is unusually high for the deep  
1323 habitats, and 25% consisted of polychaetes. The remaining fauna consisted of gastropods,  
1324 aplacophorans, and a few echinoderms. The second station was dominated by polychaetes with  
1325 few bivalves but had a high biomass due largely to echiurans (Burd, et al., in press). A third  
1326 station in the southern main basin of the Strait appeared to have a faunal composition that was  
1327 intermediate between the other two stations, albeit with a lower overall biomass and abundance  
1328 than the other two stations along with a lower organic flux to bottom sediments (Johannessen et  
1329 al., in press). These differences illustrate the wide variety of faunal types which may occur at  
1330 depth within the deep basin of the SoG, presumably related to differences in sedimentation  
1331 conditions (Burd et al., in press).

1332

1333 **2.2.3 Sand Habitats**

1334 Unlike the previous two substrate types, sand substrates are non-cohesive and, potentially, are  
1335 highly mobile. Sand habitats are abundant in areas with high energy currents and a proximate  
1336 source of either land-based or glacial deposit sands. These habitats may be depositional or  
1337 erosional, depending on the currents and the source and persistence of the sedimenting material.  
1338 In some cases where there is on-going input of sand from erosion or freshwater runoff, the area  
1339 may be net depositional with variable bottom currents. In addition, seasonal deposition of finer  
1340 substrates may occur based on water column productivity, but these deposits may be resuspended  
1341 and transported away during winter storms.

1342

1343 Sand substrates are porous and well oxygenated, often to sediment depths >10 cm; they are  
1344 subject to both diffusion and lateral seepage of oxygen and dissolved organic material. Low  
1345 porewater oxygen would be expected only in very unusual circumstances, such as may be found  
1346 in a stagnant basin with high inorganic input. Organic flux may vary greatly but the deposition of  
1347 typically fine, organic material is limited such that sediment TOC content is generally low  
1348 (<1%). Sand habitats are the most extensively bioturbated of all the habitat types, as the  
1349 sediments tend to be loosely packed, and, thus, are relatively easy to move through. Sand  
1350 habitats may be subject to considerable transport in high energy areas, so that biotic community  
1351 types and stability are directly related to the frequency and type of high energy, remobilizing  
1352 events.

1353

1354 Biotic factors in sand substrates include a high potential for bioturbation; tube-building  
1355 polychaetes and amphipods are frequently found in these substrates. Sand substrates tend to

1356 have a higher proportion of suspension feeders than deposit feeders, and epifaunal predators and  
1357 scavengers are common. While some species that are found in the mixed silt/sand habitats may  
1358 also be present in sand habitats, the strictly deposit-feeding species are typically absent or rare  
1359 (Rhoads and Young, 1970).

1360

#### 1361 **2.2.3.1 Shallow (0-30 m) sand**

1362 In the SoG, sand substrates in depths <30 m range from being semi-protected to semi-exposed to  
1363 wave and storm disrupted, and some bottom turbidity is possible. Sediment sources may be  
1364 fluvial, along-shore or onshore/offshore. Predominantly sand substrates in low to moderate  
1365 energy areas in the SoG typically include high numbers of deep burrowing bivalves, such as  
1366 horse clams (Lauzier et al., 1998) butter clams, littleneck clams (Gillespie and Bourne, 1998).  
1367 These species are common throughout BC and Alaska. Where clam populations are high, the  
1368 surface sediments are commonly littered with shell debris resulting from predation. The surface  
1369 of the sediments in shallow sand habitats may be dominated by sand dollars, sea pens or surface  
1370 bivalves such as *Tellina* spp. (Burd, 1992). Mobile predators such as small to mid-size crabs, sea  
1371 stars and drills, are common. Grazers such as small and large gastropods (such as *Gastropteron*  
1372 sp.) may be present. Epibenthic amphipods can be highly concentrated, scavenging in areas of  
1373 detrit. Polychaetes are common in sandy substrates, but tend to be dominated by mobile forms,  
1374 which may be predators or suspension feeders. Palsson et al. (2003) note that Dungeness crab  
1375 were most abundant in this depth range in the Washington State SoG (southernmost part) during  
1376 the 2001 transboundary trawl survey, although they were not surveyed in this depth range in the  
1377 SoG. However, there is an active crab fishery in the sandy sediments east of Vancouver Island  
1378 within the southern Gulf Islands. Filamentous red and green macroalgae occur in undisturbed

1379 sediments and foliose red algae may be found, drifting, in the deeper areas in this habitat. In  
1380 more exposed areas (or where herbivorous predators such as sea urchins are abundant),  
1381 encrusting coralline algae may predominate. Eelgrass beds occur in clean water, relatively low  
1382 energy (i.e. sheltered) areas in these sand habitats. While the epiphytic fauna in eelgrass beds in  
1383 this habitat may be similar to that found in the shallow silt/sand habitat, the infaunal  
1384 communities will be composed primarily of suspension feeders rather than deposit feeders. In the  
1385 deeper areas of this habitat, in specific and spatially limited patches, deep burrowing geoduck  
1386 populations may be present.

1387

1388 An example of the shallow sandy habitat is found in Boundary Bay, which is a typical sand  
1389 beach in the southern SoG (Fig. 1). Burd et al. (1987) identified 200 taxa as part of a study on  
1390 the distribution and abundance of macrofauna in Boundary Bay. Most of the shallow, sand  
1391 substrate stations were dominated numerically by nematodes plus several species of bivalves,  
1392 amphipods and echinoderms. Polychaetes were less prominent than the aforementioned taxa.  
1393 The authors note that their study illustrates the spatial heterogeneity of shallow subtidal benthic  
1394 communities. Cluster analysis of the abundance data showed considerable dissimilarity between  
1395 and within sand stations, particularly when compared with similar analyses for deep water  
1396 benthic communities in BC (Brinkhurst, 1987). Using visual counts of specific large macrofauna  
1397 along transects in Boundary Bay, Swinbanks and Murray (1981) concluded that in predominately  
1398 sand substrates, tidal exposure was an important factor delineating communities. Burd et al.  
1399 (1987) suggest that the spatially and seasonally patchy distribution of eelgrass in Boundary Bay  
1400 (Swinbanks and Murray, 1981) is a potential factor related to the distribution patterns of species.

1401

1402 Another example of a relatively unimpacted shallow sandy habitat was studied on the western  
1403 margin of the Strait, just north of Saanich Inlet (Boatswain Bank). This location was discussed  
1404 earlier (under shallow silt/sand habitats; section 2.2.2.1), and included both habitat types along  
1405 an on-shore/offshore gradient, with sandy substrates in the shallower subtidal region.. Epifaunal  
1406 biota and macroalgae (Seacology et al., 2001) and infauna (Burd and Glaholt, 2000) were  
1407 surveyed along several transects perpendicular to shore at the proposed SoG crossing pipeline  
1408 landfall site. Eelgrass beds and other macroalgae were mapped more extensively in the area by  
1409 video survey (Archipelago Marine Research Ltd., 2000). The sandy stations were all found at  
1410 less than 10 m depth, below a typical cobble intertidal beach, and were dominated by infaunal  
1411 bivalves and crustaceans, along with polychaetes and a few echinoderms within patchy eelgrass  
1412 beds. The authors noted that juvenile fauna were numerous, which would be consistent with the  
1413 concept that eel-grass beds are important nursery grounds for many types of fauna (Archipelago  
1414 Marine Research Ltd., 2000).

1415

#### 1416 **2.2.3.1 Mid-depth (30-100 m) sand**

1417 Mid-depth sand habitats in the SoG are subject to a variety of wave exposures, are often affected  
1418 by currents or swells and may be influenced by large storm events. Bottom turbidity is usually  
1419 low in these sand substrates, however, because these sediments are heavy and settle quickly. The  
1420 biota found include burrowing bivalves that may be smaller, on average, than those found in the  
1421 shallower sand habitats. Burrowing polychaetes and mat-forming tubicolous polychaetes occur  
1422 in mid-depth sand habitats, as do ophiuroids, although these are found in lower abundance than  
1423 in finer grained habitats (Burd et al., 2000a; McPherson et al., 2007a). Crustacean fauna are an  
1424 important component in these habitats and depths, including Dungeness crabs (Palsson et al.,

1425 2003). Sea pens and sea whips are found in higher current areas (Burd, unpublished data) and  
1426 some attached forms of invertebrates (e.g. hydroids) occur on larger fauna and debris (V.  
1427 Macdonald, pers. comm. Biologica Environmental Services Ltd, Victoria, BC).

1428

1429 The mid-depth sandy habitat type example from the SoG is the Ecological Reserve 67, located in  
1430 Satellite Channel. Although an Ecological Reserve, this area was neither regulated nor subject to  
1431 enforcement until several years ago. However, the only major impact on the area has been  
1432 bottom trawling and, despite the known biotic changes that can occur in areas of concentrated  
1433 bottom trawling (Engel and Kvitek, 1998; and see Conservation Biology issue 12: Vol. 6, 1998),  
1434 a reconnaissance survey in 2000 for the proposed GSX pipeline suggested that the benthic biota  
1435 are typically diverse and abundant compared with other areas of the SoG (Burd et al., 2000a;  
1436 Burd et al., in press). Fauna in the reserve are dominated by bivalves and a mixture of mobile  
1437 and non-mobile polychaetes (epibenthic and burrowing, free-living and tube-dwelling); the latter  
1438 group may have comparable or lower abundances than the bivalves. The fauna also includes  
1439 abundant crustaceans but relatively few gastropods. Echinoderms are rare which may be because  
1440 large, mobile organisms with patchy distribution are not readily sampled using the methodology  
1441 (grabs) of the studies cited here or, alternatively, the low abundance may reflect the adverse  
1442 effects of bottom trawling. Older studies of the same area suggest that echinoderms were more  
1443 common in the late 1960s (Ellis, 1970; 1971), before bottom trawling was frequent in this area.  
1444 Ophiuroids also are relatively rare, which may be related either to the non-selective deposit-  
1445 feeding habits of these animals and the lower organic content of sediments or, again, to the  
1446 damage caused to these near-surface fauna by bottom trawling. Mats of tube-dwelling  
1447 polychaetes *Galathowenia oculata* and *Owenia fusiformis* were abundant in the Satellite Channel



1448 area in the late 1960s (Ellis, 1970, 1971), but were not abundant in 2000 (Burd et al., 2000a).

1449 Bottom trawling is likely to cause disruption of tube mat structures on the sediment surface.

1450 Largely because mid-depth sand habitats typically have moderate sediment oxygen levels and

1451 low turbidity, hydroids are found attached to shelled organisms on or just below the surface

1452 (Burd et al. 2000a), and may be an important component of the filter feeding biota of these

1453 habitats.

1454

1455 During the 2001 PICES Burrard Inlet workshop, fauna were sampled from a mid-depth sand

1456 habitat reference station outside the sill of Howe Sound (PICES, 2001; Je et al., 2003). Results

1457 using similar sampling methods showed species richness at this station was similar to that of

1458 samples from the ER67 Satellite Channel stations (Burd et al., 2000a; Je et al., 2003). Faunal

1459 abundance, however, was much higher in the Satellite Channel samples, as there were fewer

1460 bivalves present in the Howe Sound location. Polychaetes, rather than bivalves, were dominant at

1461 the Howe Sound location. A range of epifaunal types (8 taxa) are listed in Bernard (1978) to

1462 occur at depths of 20-100 m in sandy areas sampled in the SoG.

1463

#### 1464 **2.2.3.1 Deep (>100 m) sand**

1465 Deep sand habitats only occur, typically, in moderate to high current (erosional) areas. In low

1466 current areas, the deposition of fine marine detritus would cover the sands eventually. The epi-

1467 benthic list of Bernard (1978) includes 4 taxa for the 100-200 m depth range but only one

1468 polychaete (*Pectinaria californiensis*) is listed for the 200-300 m depth range and one

1469 scaphopod (*Dentalium rectius*) for the 300-400 m depth range. Although no other data or studies

1470 are available from such habitat types in the SoG, these sand habitats may occur in deep water in

1471 isolated areas near the southern Gulf Islands or in the northern half of the SoG (Fig. 3).  
1472 Information on the biotic communities in these habitats outside the SoG, specifically in Hecate  
1473 Strait and la Perouse Bank, is available in Burd and Brinkhurst (1987) and Brinkhurst (1987),  
1474 respectively.

1475

#### 1476 **2.2.4 Cobble, Gravel and Coarse Sand Habitats**

1477

1478 Cobble, gravel and coarse sand habitats are usually found in moderate to high energy locations.  
1479 This substrate can also occur, however, where there are coarse glacial deposits in lower energy  
1480 locations with no source of finer glacial or freshwater-derived inorganic particulates (finer  
1481 sands). These substrates can be both mobile and immobile. For example, constant deposition of  
1482 substrate material from a major land-based source would probably lead to unstable deposits  
1483 subtidally, particularly on slopes. In stable habitats, however, these substrate materials tend to be  
1484 heavy and can only be moved by high energy waves or storm events, particularly in shallow  
1485 subtidal areas. Similarly, the coarse materials are a difficult substrate for the burrowing activities  
1486 of bivalves and other fauna and, as a result, bioturbation may be limited. Because the substrate  
1487 materials in these habitats are so coarse, sediments tend to be well-flushed and oxygenated. The  
1488 benthic fauna are dominated by suspension feeders and mobile predators, particularly in high  
1489 current areas. Cobble substrates in particular are likely to have fauna similar to rocky substrates  
1490 (Section 2.2.5).

1491

1492 Bernard (1978) includes a few dominant epifauna from these habitats at various depths, but the  
1493 epifauna list is short relative to that for soft substrates due perhaps to the difficulties in sampling

1494 this habitat type. These habitats can be viewed as “intermediate”, as they are neither soft enough  
1495 for effective grab samples to be taken nor flat and smooth enough for visual transect surveys.  
1496 Much of the fauna is interstitial (ie. living between sediment particles) and there is no efficient  
1497 way to sample them. Similarly, while trawls may collect some epibenthic forms, both the nets  
1498 and the captured biota are prone to damage by cobble and gravel substrates. Bottom sampling is  
1499 further hampered by the fact that these habitats are usually very high current areas. Hence, there  
1500 is very little information about these habitats in the SoG, and none of the information available is  
1501 quantitative.

1502

#### 1503 **2.2.4.1 Shallow (0-30 m) cobble, gravel and coarse sand**

1504 In shallow depths in the SoG, these coarse substrates are found most often on high energy or  
1505 exposed to semi-protected areas, extending from the intertidal to the shallow subtidal. An  
1506 example of such a habitat is given in Seacology et al. (2001) and Burd and Glaholt (2000), but it  
1507 is noted in both studies that the cobble or gravel does not extend very far below the intertidal,  
1508 and tends to occur in patches along with coarse sand. These habitats are usually non-depositional  
1509 but may be influenced by seasonal onshore/offshore movement of material due to storm events  
1510 and strong currents. In addition, periodic storms may lead to patches of storm or tidal debris  
1511 (organic and inorganic) which are usually transitory. If these shallow habitats are not too high  
1512 energy, seasonal macroalgae such as the brown algae *Laminaria*, *Costaria* and *Desmarestia* may  
1513 be dense along with patches of bull kelp (Seacology et al., 2001) along with epifaunal grazers. A  
1514 variety of mobile epifauna are found in these habitats, including amphipods, sea stars,  
1515 nudibranchs, gastropods, echinoids and large mobile polychaetes, shrimp and crabs, and is also  
1516 noted to be a nursery habitat for juvenile Pacific cod. Sessile invertebrates attached to the larger

1517 substrate particles include bryozoans, hydrozoans, small sponges and anemones. If the sand  
1518 content is high, deep burrowing bivalves may occur. However, in larger particle mixes (gravel,  
1519 small cobble), near-surface bivalves may be common, and shell debris extensive. Coarse,  
1520 unconsolidated habitats, if stable, can have extensive macroalgal growth seasonally, with all the  
1521 associated grazing, epiphytic and epifaunal biota associated with it. Typically, this may include  
1522 extensive bryozoan (in shallow, near-subtidal) and hydrozoan growth, shrimp, crabs, amphipods  
1523 and other crustaceans, nudibranchs, gastropods, sea-stars and sea-urchins, with anemones, small  
1524 sponges and tunicates attached to larger, stable debris. One common bivalve which can be seen  
1525 “walking” through coarse sands is *Tellina* sp., which can be found intertidally to subtidally in  
1526 Hecate Strait and throughout southern Alaska, BC and Washington State. Other, larger  
1527 echinoderms may be present in coarser debris, such as the sea-cucumber *Parastichopus* sp.

1528

#### 1529 **2.2.4.2 Mid-depth (30-100 m) cobble, gravel and coarse sand**

1530 Cobble, gravel, and coarse sand habitats below 30 m water depth are rare in the SoG, with the  
1531 exception of very high energy environments such as tidal channels, on fjord sills, and high  
1532 current areas. Because of the size of the substrate particles, these habitats are relatively  
1533 physically stable, although they may be mobile in rare, large storm events. Suspended particles  
1534 may be extensive, given the high energy nature of these habitats. Generally, the faunal  
1535 community in these habitats includes mobile epifauna (e.g. sea stars, nudibranchs, gastropods,  
1536 amphipods), as well as ‘surface film’ grazers and attached forms (e.g. hydroids, small sponges,  
1537 anemones) on the larger sediment particles (see Farrow et al., 1983).

1538

1539 An example of mid-depth coarse habitats is the sill of Knight Inlet, which is located immediately  
1540 north of the SoG. The Knight Inlet sill is also a tidal channel, with coarse sand, gravel and large  
1541 boulders which can be moved by the strong tidal currents (see Farrow et al., 1983). Tunnicliffe  
1542 and Syvitski (1983) describe how large gorgonian corals attached to boulders provide “windage”  
1543 which contributes to the transport of boulders in this area. The authors found that these rare  
1544 habitats may contain typical rock cliff epifauna occurring in patches but, unlike cliff fauna, the  
1545 forms are usually encrusting which may be related to the potential physical damage caused by  
1546 the moving boulders and high currents. The distribution of the large planktivorous corals was  
1547 patchy but the organisms were most concentrated on the sill crest, where the zooplankton were  
1548 visually dense (Tunnicliffe and Syvitski, 1983). The level of heterogeneity within this type of  
1549 habitat will determine the abundance of small mobile fauna that like to hide, such as shrimp and  
1550 small crabs.

1551  
1552 Although the extensive outfall monitoring program in outer Burrard Inlet focused on soft  
1553 substrate, video assessment of the nearfield substrate revealed the presence of cobble, gravel and  
1554 coarse sand substrate (CORI, 2002). Flocculant levels were high in the water column, reducing  
1555 visibility. However, large concentrations of the anemone *Metridium senile* suggested  
1556 opportunistic utilization of the suspended organic material (CORI, 2002). Visual surveys by the  
1557 Victoria Capital Regional District describe the 40-60 m depth range off southern Victoria near  
1558 Clover Point (just outside the SoG, in Juan de Fuca Strait) as cobble-gravel, with extensive horse  
1559 mussel and scallop growth (Capital Regional District, 2000). Bernard (1978) listed 2 bivalve  
1560 species, (*Glycymeris subobsoleta* and *Mysella tumida*) sampled by trawl from gravel substrates  
1561 and 6 different species found in rock/cobble substrates.

1562

1563 **2.2.4.3 Deep (>100 m) cobble, gravel and coarse sand**

1564

1565 These coarse grained habitats seem to be rare in the deeper parts of the SoG (Fig. 3). It is likely  
1566 that these habitats are limited to the few deep, strong tidal channels in the SoG at the north and  
1567 south end (Section 1.2) and to areas where debris resulting from cliff erosion has settled at the  
1568 foot of steep slopes. These areas have been observed, occasionally, using a submersible (Burd,  
1569 unpublished data) and, although most fish farms in BC are located outside the SoG, information  
1570 on these habitats under fish farms in the fjords of the SoG may also be archived in ROV video  
1571 footage maintained by the provincial Ministry of Environment.

1572

1573 There is very limited information about these coarse habitats and associated biota in depths >100  
1574 m within the SoG. However, it is expected that the faunal communities would be of similar  
1575 composition to those described earlier for the mid-depth coarse habitat. The only caveat is that at  
1576 these depths, it is likely that organic flux to the bottom is reduced, so that there may not be as  
1577 much labile organic suspended material available for bottom organisms. Bernard (1978)  
1578 describes invertebrate epifauna from trawls conducted at 100-200 m depths in gravel habitat type  
1579 and lists the same two species found in the 20-100 gravel substrates, the bivalve *Glycymeris*  
1580 *subosoleta* and the crustacean *Munida quadrispina*. The author lists no species for sampling  
1581 conducted in gravel substrates >200 m. Invertebrate species were more abundant in the  
1582 rock/cobbles substrate than in the gravel substrate, but only the cloud sponge *Aphrocallistes*  
1583 *vastus*, was reported from the rock/cobbles substrate type at >200 m depths. As noted earlier,

1584 archived information on videos from deep ROV work related to fish farms may be one of the  
1585 best sources of epifaunal data available.

1586

1587

## 1588 **2.2.5 Rock (consolidated) Habitat**

1589

1590 In exposed coastal areas, these substrates are subject to very high wind and wave exposure  
1591 and/or tidal currents, preventing any deposition. However, in isolated basins such as fjords, the  
1592 steep sides prevent accumulation from sedimentation regardless of current conditions. Some  
1593 island archipelagos, with no freshwater or nearby glacial deposits, can retain rocky substrates in  
1594 lower energy habitats. Although high levels of suspended organic particles occur, depending of  
1595 the current regime and organic input, organic flux to the sediments is virtually nil.

1596

1597 Rocky habitats are abundant in the SoG and Levings et al. (1983) note that rocky and sandy  
1598 shores combined make up 88% of the total length of the shoreline (shoreline consists of the  
1599 intertidal and subtidal habitats  $\leq 20$  m), while the area of rocky substrate accounts for ~25% of  
1600 the total area (see Section 1.3.1). Many of the SoG's mainland fjords have extensive, near-  
1601 vertical rocky cliffs, limiting the fauna to those that can attach to vertical rock and that can  
1602 tolerate sediment deposition. These rock wall communities are dominated by sessile filter  
1603 feeding invertebrates or mobile scavengers and predators. Tidal currents in these habitats are  
1604 usually low due to the near-vertical walls which don't "channel" or intensify tidal surges.

1605

### 1606 **2.2.5.1 Shallow (0-30 m) rock (consolidated)**

1607  
1608 The diversity and coverage of rocky shoreline communities is dependant on exposure to waves,  
1609 freshwater, salinity, light and currents and is, therefore, seasonally variable. The presence of  
1610 crevices or heterogeneous structure for hiding and attachment also affects both the plants and  
1611 invertebrates found in these shallow rock habitats. The bottom water in these habitats is usually  
1612 highly oxygenated. If there is a rich supply of suspended particulate material, these areas can be  
1613 ~100% covered by sessile invertebrates and plant growth. Seasonal macroalgal cover of  
1614 filamentous and bladed red, green and brown algae is extensive in the upper photic zone, with  
1615 foliose reds commoner in slightly deeper areas (i.e. >10 m).  
1616  
1617 The fauna found in these habitats, both sessile and mobile forms, tends to be relatively consistent  
1618 throughout the BC coast. The diverse fauna in these habitats includes bivalves, calcareous tube  
1619 worms, ascidians, bryozoans, hydrozoans, small sponges, as well as echinoderms and  
1620 crustaceans. Because these rocky habitats have been so well described by scuba surveys at these  
1621 shallow depths, the flora and fauna are not described in detail herein (e.g.  
1622 [http://ilmbwww.gov.bc.ca/lup/coastal/north\\_island/cortes/docs/2-description.pdf](http://ilmbwww.gov.bc.ca/lup/coastal/north_island/cortes/docs/2-description.pdf); Levings et al.,  
1623 1983 and references therein). An example of a shallow rock habitat just outside the SoG is Race  
1624 Rocks, near Sooke, BC. Race Rocks, a tidally-exposed rocky outcrop in a “clean” environment  
1625 which has been well studied using SCUBA. The area has a remarkably rich and diverse flora and  
1626 fauna (see Wright and Pringle, 2001 for references) and is a federal marine protected area. The  
1627 invertebrate fauna tolerates strong currents and high wave exposure and includes abundant  
1628 barnacles, goose-neck barnacles, and mussels, as well as a variety of anemone species, surface-  
1629 grazing gastropods, mobile predators such as sea-stars, nudibranchs, crabs and gastropods.



1630

1631 Shallow rock habitats may be structurally heterogeneous as a result of algal growth and also  
1632 from faunal communities such as mussel beds. Up to 300 species have been identified inhabiting  
1633 the interstices of established mussel beds (Seed and Suchanek, 1972; Suchanek, 1979) and  
1634 species richness has been shown to increase with increasing age and thickness of the mussel bed  
1635 (Asmus, 1987; Jamieson et al., 1999; Ragnarsson and Raffaelli, 1999; Smith et al., 2006).

1636

1637 In the deeper, high current areas of shallow rock habitats, bull kelp can form dense forests which  
1638 modify currents and light penetration and provide important refugia for fish, as well as food for  
1639 sea urchins and other grazers. Sea urchins are known to be a key species which controls and  
1640 modifies algal community associations in near-shore rocky habitats on the west coast of North  
1641 America (Paine and Vadas, 1969; Duggins, 1981). Abalone may play a similar role but tend to  
1642 be less widely distributed in BC coastal waters than are sea urchins due to excessive fishing  
1643 pressure over the years ([http://www.dfo-mpo.gc.ca/species-especes/species/species/northernAbalone\\_e.asp](http://www.dfo-mpo.gc.ca/species-especes/species/species/northernAbalone_e.asp)).

1645

#### 1646 **2.2.5.2 Mid-depth (30-100 m) rock (consolidated)**

1647

1648 Mid-depth rock habitats in the SoG typically have moderate to steep slopes; accumulation of  
1649 deposited material is unlikely to occur on steep slopes but pockets of deposition may occur on  
1650 lesser slopes. These habitats are exposed to limited, or no, wave exposure, while levels of tidal  
1651 currents vary. Bottom water renewal, and therefore bottom water oxygenation, in these habitats

1652 in the SoG is variable and depends on the physical topography and, in fjords, also depends on the  
1653 depth of the sill.

1654

1655 Because these habitats can only be studied using ROVs or submersibles, they are, therefore, less  
1656 well studied than soft substrate habitats at comparable depths. The majority of this research in  
1657 the SoG was conducted in the early 1980s, when the research submersible PICES IV was  
1658 available through the Canadian Department of Fisheries and Oceans. Much of this research is  
1659 published (e.g. Tunnicliffe, 1981; Levings et al., 1983; Tunnicliffe and Wilson, 1988) and  
1660 additional, unpublished information is archived in video or still photographic form (Tunnicliffe,  
1661 unpublished; Burd, unpublished). The following general descriptions of the faunal communities  
1662 in the mid-depth rock habitats of the SoG are based on both sources of data.

1663

1664 The spatial cover by invertebrates in the mid-depth rock habitats does not vary as much  
1665 seasonally as it does in shallow subtidal areas. However, there may still be some encrusting  
1666 coralline algae present at the shallow end of this depth range, depending on light penetration (e.g.  
1667 Farrow et al., 1983; Spalding et al., 2003). Rather, the spatial cover by invertebrates declines  
1668 with increasing depth and decreasing oxygen levels in the water. Examples of the mid-depth  
1669 rock habitat are the rock cliff walls of fjords in the SoG. These mid-depth habitats contain a  
1670 number of species, such as eel-pouts, that are more common in the deep sea. Similarly, sea fans  
1671 (gorgonians, soft corals) are common on the walls of some of the SoG inlets (Tunnicliffe, 1981;  
1672 Tunnicliffe and Wilson, 1988) but are also found when sampling in the deep water off the  
1673 continental shelf. Huge glass sponges, normally associated with polar or deep seas, are also  
1674 common in mid-depth rock habitat in the SoG fjords (Tunnicliffe, 1981; Burd, PICES IV–

1675 unpublished data). Tunnicliffe (1981) describes tube worms, sponges, brachiopods, cup corals,  
1676 extensive gorgonian sea fans, anemones and colonial tunicates as some of the dominant sessile  
1677 organisms on the vertical rock walls. Some of the larger sponge and erect coral growths are  
1678 expected to be very old, as these habitats are typically less susceptible to physical damage than  
1679 are level bottom habitats.

1680 Tunnicliffe and Wilson (1988) describe the distributions of 3 species of brachiopods from  
1681 Knight, Jervis and Saanich inlets; brachiopods are a ubiquitous group reaching extremely high  
1682 densities (average density of  $190/m^2$ , maximum density of  $945/m^2$ ) at depths  $>30$  m on the cliff  
1683 walls of the fjords. Depth ranges were noted for each species of brachiopod. All brachiopod  
1684 species seem to be relatively tolerant of low oxygen and a species in Saanich Inlet was found to  
1685 be highly tolerant of periodic low oxygen levels down to 0.1 ml/L. Another brachiopod species  
1686 from Saanich Inlet was found in abundance in high energy and/or high suspended sediment  
1687 conditions. Thus, brachiopods are an important structural component of mid-depth cliff faunas  
1688 and may be good indicators of sedimentary conditions. In contrast to brachiopods, bivalves are  
1689 almost absent on the vertical cliff walls, suggesting that they do not settle on vertical surfaces. In  
1690 addition, as a group they do not seem to be particularly tolerant of low oxygen (see also Burd,  
1691 2006).

1692  
1693 Several mobile crustaceans are common on, or near, the rocky cliff walls of the fjords at mid-  
1694 depth. These areas encompass the prevailing prawn fishery habitats, as the larger pandalid  
1695 species tend to be abundant in the rocky crevices and on larger, upright epibenthos. Predatory  
1696 crabs are less common in this depth range than in the shallow rocky cliff areas, (Burd,  
1697 unpublished), however, a small anomuran crab (*Munida quadrispina*), with feeding and habitat

1698 requirements similar to prawns co-exists with the prawns on the cliffs (Burd and Brinkhurst  
1699 1984). Examination of prawn catches and habits of prawn fishermen in a series of coastal fjords  
1700 in the SoG in 1983/84 (Burd, unpublished) made it clear that when *M. quadrispina* were  
1701 dominant, this necessitated a change in the location for setting traps.

1702

1703 Saanich Inlet and Howe Sound, as noted earlier, can experience severe annual stagnation and this  
1704 can lead to mass mortalities of sedentary cliff fauna (Tunncliffe, 1981) as well as mobile forms  
1705 such as prawns and *Munida quadrispina* (Burd and Brinkhurst, 1984; Jamieson, 1988).  
1706 Tunncliffe (1981) described a high biodiversity in the mid-water cliff assemblage of Saanich  
1707 Inlet, however, despite annual low oxygen, *M. quadrispina* is usually far more abundant in  
1708 extreme habitats, such as the very low oxygen areas (~0.1ml/L) in Saanich Inlet (Burd and  
1709 Brinkhurst, 1984) than in areas with higher oxygen levels. The higher abundance (and lack of  
1710 normal territorial and hiding behaviour) of the crabs has been speculated to be related to a lack of  
1711 predators in these extreme habitats (Burd and Brinkhurst 1984), whereas the tolerance of very  
1712 low oxygen areas is due to unusual respiratory and gill adaptations (Burd, 1985, 1988). In  
1713 addition, the pelagic amphipod *Orchomene obtusens* is found in extremely high numbers on, or  
1714 near, the rocky cliffs in hypoxic to anoxic conditions in Saanich Inlet (De Robertis et al., 2001),  
1715 where it is extremely efficient at consuming any detrital animal tissue used as bait in traps (Burd,  
1716 unpublished data).

1717

1718 Farrow et al. (1983) describe the fauna of the cliff walls in Knight Inlet along vertical cliff  
1719 transects which include the mid-depth zone. The along-inlet differences in faunal structure were  
1720 compared with a suspended particulate gradient which typifies the faunal changes that are likely

1721 to occur in areas of high, moderate, and low bottom turbidity from glacial runoff. In the high  
1722 turbidity areas, the authors describe the dominant suspension feeders as sabellid worms and  
1723 brachiopods (see also Tunnicliffe and Wilson, 1988) which take small particles ( $<8 \mu\text{m}$ ).  
1724 Crinoids and gorgonian corals are more prevalent in the moderate turbidity areas and take larger  
1725 particles, while barnacles and glass sponges predominant where turbidity is low. In general, the  
1726 turbidity, oxygen and organic carbon content of suspended particulates within these habitats play  
1727 a significant role in determining which species will dominate. For example, brachiopods are  
1728 tolerant of relatively low oxygen conditions and can also tolerate relatively high turbidity.  
1729 Passive feeders, such as sponges, require some current movement for adequate feeding, but may  
1730 be tolerant of low oxygen (e.g. Tunnicliffe, 1981), and are usually found in deeper regions in  
1731 more quiescent waters (Tunnicliffe, 1981; Farrow et al., 1983) with limited sediment deposition  
1732 (Farrow et al., 1983 and see below).

1733  
1734 A bottom hexactinellid sponge reef has been recently discovered at an unprecedented shallow  
1735 depth of about 60 m near the sill of Howe Sound (see Cook et al., in press). Most of these reefs  
1736 in the Strait are deeper than 120 m, making this location unusual. This reef has not been visually  
1737 surveyed yet. A description of other, deeper reefs in the Strait is given in the next section.

1738

### 1739 **2.2.5.3 Deep (>100 m) rock (consolidated)**

1740

1741 While deep subtidal rock habitats in the main basin of the Strait of the Georgia are mostly  
1742 confined to elevated rocky outcrops on the bottom of the basin (evident in detailed multibeam  
1743 and side-scan sonar transects e.g. Conway et al., 2007), these habitats are often dominant in

1744 many of the steep-sided fjords. Many of the SoG fjords are much deeper (up to 800 m) than the  
1745 adjoining continental shelf (<400 m deep), with extensive rock cliffs. The same limitations for  
1746 studying the mid-depth rock habitats, discussed earlier, apply to these much deeper habitats.

1747  
1748 In deep rock habitats that are “flushed”, bottom currents are generally low to moderate. Bottom  
1749 water oxygen is likely to be moderate. Spatial cover of sessile invertebrates on these “flushed”  
1750 rock substrates is moderate to low, declining with increasing depth and decreasing oxygen levels  
1751 and is also related to current levels. The faunal composition does not necessarily change  
1752 significantly from that described for mid-depth rock habitats except that, as suspended organic  
1753 material and oxygen levels decline with increasing depth, spatial coverage may decrease and  
1754 some organisms or trophic forms may decline while other, more tolerant forms increase. For  
1755 example, as noted earlier, prawns decline with increasing depth and anemones such as *Metridium*  
1756 *senile* are not found below 80-100 m (Tunncliffe, 1981; Burd, unpublished data). The faunal  
1757 community may include calcareous tube worms, brachiopods, ascideans, hydrozoans, small  
1758 sponges, boot and cloud sponges, gorgonian and small corals, large plumose anemones and  
1759 tunicates.

1760  
1761 It should be noted that deep rock habitats in the SoG are also found on the walls of isolated  
1762 fjords in stagnant basins. The water column in the deep rock habitats in the fjords may flush  
1763 seasonally or only occasionally. Generally, the rock may be too steep for sediment accumulation  
1764 but small pockets of organic material may accumulate in crevices and become suboxic or anoxic  
1765 with filamentous bacterial mats. In these low current areas, the rock is usually minimally  
1766 colonized with numerous areas of bare rock. As mentioned for mid-depth rocky areas, the fauna

1767 in these deep stagnant areas may include small anemones, encrusting sponges and brachiopods,  
1768 as well as specialized mobile predators (e.g. amphipods, *M. quadrispina*) (Burd and Brinkhurst,  
1769 1984).

1770 An interesting example of the deep, rocky habitat is the relatively recently discovered deep rocky  
1771 outcrops or reefs in the SoG that are covered in hexactinellid sponges (predominantly  
1772 *Heterochone calyx* and *Aphrocallistes vastus*) or in a few cases, scleractinian coral reefs  
1773 (*Lophelia pertusa*) (Conway et al., 2007). There are nine confirmed glass sponge reef complexes  
1774 in what Thomson (1998) describes as the central Georgia Basin (Fig. 1). Each of these sites has  
1775 been surveyed using multibeam acoustics and ground truthed using remote video techniques by  
1776 the Geological Survey of Canada. There are a further 3 sponge reefs which have been located by  
1777 multibeam and seismic surveys but which have not yet been visually examined using video  
1778 (Conway et al., 2007). Of the nine reefs which have been visually surveyed, only three are in  
1779 good health, with consistent areas of live reef-building sponges (Cook et al., in press). The three  
1780 healthy reefs are located on rock pinnacles well above the surrounding seafloor, where bottom  
1781 trawling is not feasible. The other six appear to have suffered extensive mechanical damage  
1782 resulting in large areas of fragmented sponge skeleton, with 3 reefs showing some evidence of  
1783 re-growth. (Cook et al., in press). ). Conway et al. (2007) concluded that there has been  
1784 considerable damage to the reefs in the SoG from trawling and possibly from ocean dumping and  
1785 increased siltation in the southern areas. There is a marked difference in terms of abundance and  
1786 diversity of rockfish on the healthy and damaged reefs, illustrating that these are likely important  
1787 refugia for deep reef fish. An ecological description of these reefs is in Cook et al. (in press),  
1788 including the current state of their health and faunal associations.

1789

1790 It is well documented that hexactinellid sponge communities, such as those found in deep rock  
1791 habitats in the SoG, modify the environment around them. Bathyal environments in particular are  
1792 enriched by enhanced supplies of organic matter associated with sponges and their spicule mats  
1793 (Bett and Rice, 1992). In the Antarctic, Barthel, (1992) documented species-rich associations of  
1794 sponges in areas of sponge spicule mats. These reefs trap fine sediments and provide habitat for  
1795 annelid worms, bryozoans, bivalves, gastropods, rockfish, crabs, shrimp, prawns, sea stars, sea  
1796 urchins and ophiuroids. In other areas of the world, hexactinellid sponges provide habitats for  
1797 new and rare species, including numerous species of shrimps in the Bahamas (Berggren, 1993),  
1798 Hawaii (Baba, 1983), New Zealand and South Africa (Bruce and Baba, 1973), and in the East  
1799 China Sea (Hayashi and Ogawa, 1987). Their locally limited distribution and potential biological  
1800 importance as refugia in the SoG warrant protection (Conway, 1999; Conway et al., 2001;  
1801 Krautter et al., 2001).

1802  
1803 Underwater cables provide hard substrate in deep water, albeit of anthropogenic origin. Levings  
1804 and McDaniel (1974) describe encrusting macro-invertebrates collected off a deep-water  
1805 telephone cable across the main basin of the SoG. This habitat appears to be a “refugia”  
1806 containing fauna that are found on the steep rocky cliffs of the surrounding basin shoreline. The  
1807 authors note that most of the deeper, hard-substrate species such as sponges, brachiopods and  
1808 gorgonian corals were not present on the cables on the eastern side of the SoG (Point Grey),  
1809 probably due to heavy sedimentation from the Fraser River. Even in these high sedimentation  
1810 areas, however, several anemones, such as the ubiquitous and relatively tolerant *Metridium*  
1811 *senile*, were found on the cables.

1812



### 1813 3. Anthropogenic Influences

1814

1815 Section 2 reviewed invertebrate communities likely to occur in a variety of undisturbed habitats  
1816 (different depths and substrates) within the SoG. In this section, changes to habitats and  
1817 invertebrate fauna found in areas of anthropogenic influence are examined and placed within the  
1818 context of background biotic conditions in the SoG. Following a brief summary of  
1819 anthropogenic sources and recognized influences of the type of major sources in the SoG,  
1820 additional detail is provided on each source including case studies where appropriate. It should  
1821 be noted that while input from some anthropogenic sources may affect intertidal or shallow  
1822 subtidal areas, most of the major discharges into the SoG are deeper than the shallow subtidal  
1823 (i.e. >30 m) and, consequently, habitats monitored for anthropogenic change also tend to be >30  
1824 m depth (mid- to deep subtidal).

1825

1826 The primary sources of anthropogenic influence in the SoG are municipal waste water outfalls  
1827 (marine and along the Fraser River), ocean dumping sites (dredged material primarily from  
1828 Burrard Inlet and terminal areas along the eastern margin of the southern Strait), pulp and paper  
1829 mills, as well as runoff and discharges from agriculture and other industries along the Fraser  
1830 River and Burrard Inlet. Localized sources of anthropogenic influence to marine habitats within  
1831 the SoG include a small number of fish farms in several mainland fjords, log-booms, marinas,  
1832 loading docks for industry, and stream runoff. While a large number of beach and near-shore  
1833 shellfish aquaculture sites are located in the SoG, research into the potential impacts of these  
1834 farms on benthic habitats and invertebrate community structure started only recently (e.g.  
1835 Carswell et al., 2006) and, hence, the potential impact of these farms is largely unknown.

1836 Although the biotic effects of these localized small inputs can be varied and difficult to  
1837 encapsulate, available studies on these inputs are summarized briefly in this review (and see  
1838 Levings et al., 1983).

1839 Although the majority of the anthropogenic influences in the SoG include an organic enrichment  
1840 component, virtually all of these influences also include some level of sediment contaminants  
1841 which can make it difficult to determine causality. A huge literature on sediment and pore-water  
1842 toxicity, much of it laboratory-based, illustrates the on-going struggle with these issues in the  
1843 scientific community (Wang and Chapman, 1999; Burgess, 2000; Long et al., 2001). Burrard  
1844 Inlet, the major harbour for Vancouver, provides an example of a body of water in the SoG that  
1845 is subject to numerous sources of anthropogenic input. The proceedings of an international,  
1846 cooperative research workshop in Burrard Inlet (Stehr and Horiguchi, 2001) include a summary  
1847 of the discharges and contaminant sources in the inlet (Levings and Samis, 2001). This inlet  
1848 receives the discharge from a major primary-treatment municipal wastewater outfall, about 32  
1849 combined sewer overflows (CSOs) (GVRD, 2004), and 36 permitted industrial or municipal  
1850 discharges (Levings et al., 2004). Several of the more isolated sections (or arms) of Burrard Inlet  
1851 are considered to be severely chemically polluted by hydrocarbons (Yunker et al., 1999) and  
1852 organically enriched (Burd and Brinkhurst, 1990). The multitude of discharges, along with  
1853 complex hydrographic conditions, has made the design of monitoring programs for specific  
1854 discharges in the Inlet challenging (c.f. McPherson et al., 2007b). Similarly, Howe Sound has  
1855 been subject, historically, to notable industrial inputs including a chlor-alkali plant (mercury  
1856 discharge) and a copper mine with contaminated tailings and acid drainage issues which are still  
1857 evident many years after cessation of operations (Hagan et al., 2004). Contaminant inputs and

1858 transport from these sources were reviewed by Macdonald and Crecelius (1994), West et al.  
1859 (1994) and see Johannessen et al. (in press).

1860 Despite the confounding influences described above, however, certain patterns of benthic faunal  
1861 response seem to be common to all organic enrichment inputs in British Columbia regardless of  
1862 contaminant input (Cross, 1990; Burd, 1997; Brooks, 2001; Burd 2003a,b,c; Cross et al. 2005;  
1863 Golder Associates Ltd., 2005; Burd, 2006; McPherson et al., 2007a, b; EEM monitoring data  
1864 [www.ec.gc.ca/eem/english/PulpPaper/default.cfm](http://www.ec.gc.ca/eem/english/PulpPaper/default.cfm); ).

1865 Biotic responses in marine sediments to conditions resulting from extreme organic loading have  
1866 been described by Pearson and Rosenberg (1978). Based on this model, when sulphides are high  
1867 and/or sediments are anoxic to depth, most fauna disappear. When these sediment conditions  
1868 occur, white fibrous mats of sulphur-fixing bacteria (e.g. *Beggiatoa* spp.) may become extensive  
1869 on the seafloor. In addition to high sulphides, however, the bacteria need oxygen from the  
1870 overlying water for metabolism and, therefore, these mats occur only at the oxidation-reduction  
1871 (redox) boundary (Møller et al., 1985), making them a good indicator of underlying anoxic  
1872 sediments or, in rocky areas, of an anoxic near-bottom boundary layer. In fact, the presence and  
1873 extent of *Beggiatoa* mats is used as a monitoring indicator of benthic condition for fish farms in  
1874 BC (MWLAP, 2002). The few organisms that can survive, or sometimes even thrive, in these  
1875 conditions include certain mobile epibenthic forms such as demersal amphipods and squat  
1876 lobsters (Burd and Brinkhurst, 1984), as well as burrowing organisms that can maintain access to  
1877 the oxygenated overlying water, some of which may have a high tolerance to sulphide (Brooks,  
1878 2001). Despite these organisms, however, infaunal production is typically low in extreme  
1879 environments due to loss of most of the macrofauna and energetic constraints on microfauna

1880 utilizing energy resources without available oxygen (Emerson and Hedges, 2003). In rocky  
1881 habitats, most fauna will disappear, with the possible exception of some tolerant cup corals  
1882 (Tunncliffe, 1981). Examples of benthic environments in the SoG where anthropogenic inputs  
1883 causing these conditions may arise or have been recorded include municipal wastewater outfall  
1884 receiving environments (Capital Regional District 2003; 2004; 2005 and  
1885 [www.crd.bc.ca/wastewater/marine/reports.htm](http://www.crd.bc.ca/wastewater/marine/reports.htm); McPherson et al., 2007a, b); log boom areas  
1886 (Conlan and Ellis, 1979; Sibert et al., 1979; Sibert and Harpham, 1979; McGreer et al., 1984),  
1887 the close vicinity of some fish farms (Brooks, 2001; Burd, 2006; Wright et al., 2007a-e), and  
1888 areas subject to pulp and paper mill effluent ([www.ec.gc.ca/eem/english/PulpPaper/default.cfm](http://www.ec.gc.ca/eem/english/PulpPaper/default.cfm)).  
1889 These extreme conditions can also occur naturally in stagnant fjord basins (e.g. Saanich Inlet,  
1890 Section 1.2).

1891

### 1892 **3.1 Marine Outfalls**

1893 Benthic sediment and biological monitoring for the marine receiving environments of the Metro  
1894 Vancouver (formerly the Greater Vancouver Regional District GVRD) outfalls that discharge  
1895 into the SoG (Iona and Lions Gate) also encompasses the marine discharge zones of the other  
1896 three outfalls along the Fraser River (Annacis, Lulu Island and Langley - GVRD 2004). These  
1897 monitoring programs have essentially provided the bulk of present-day information about  
1898 benthic infauna and habitats along the southeastern margin of the SoG (see McPherson et al.  
1899 2007a, b). The Iona outfall monitoring grid is along the 80 m depth contour (Figure 1) straddling  
1900 the mouths of the Fraser River. The Lion's Gate monitoring grid encompasses all of the outer  
1901 Burrard Inlet to 1st Narrows (Figure 1).

1902

1903 Harrison et al. (1999), reviewing the heavy metal and organic contamination along the foreshore  
1904 of the Fraser River, found that most of the contamination in this area came from heavy  
1905 deposition of Fraser River sediments which had run the gauntlet of contamination sources.  
1906 However, at the north end of the delta, there was a fairly large historical (1962-1988) wastewater  
1907 discharge in the near shore. Harrison et al. (1999) showed that in the area of historical  
1908 wastewater discharge (which also receives about 15% of the industrial and municipal wastes  
1909 from the Fraser River), there is evidence of long term recovery in terms of organic loading, as  
1910 well as primary and secondary production of the benthos. Two moderately abundant invertebrate  
1911 indicators, the amphipod *Corophium salmonis* and the bivalve *Macoma balthica*, were selected  
1912 for measurements of biomass/production and growth, and were used to demonstrate the recovery  
1913 from basically azoic conditions (i.e. no life) to background conditions typical for the area. The  
1914 historical wastewater discharge noted above was replaced in 1988 with the Iona deep-sea outfall,  
1915 with diffusers which discharge along the slope fronting the Fraser River discharges.  
1916  
1917 The deposition model of Hodgins and Hodgins (2000) for the Iona outfall effluent solids  
1918 suggests that maximum deposition of outfall particulates occurs between 60-90 m depth along a  
1919 primarily north and secondarily south gradient away from the outfall. This model provided the  
1920 basis for a revised monitoring program for the outfall from 2000 onward (2WE Consulting,  
1921 1999). The maximum deposition zone corresponds to clear patterns in sediment chemistry and  
1922 geochemistry, including moderate organic enrichment (Burd, 2003b). The long-term monitoring  
1923 data for Iona (see McPherson et al., 2007a) clearly show subtle changes in biotic conditions  
1924 within a 3 km zone north of the outfall, which corresponds to the maximum deposition zone for  
1925 outfall particulates (Hodgins and Hodgins, 2000). Within this same area, clearly related to the

1926 outfall, there is low to moderate biotic impoverishment (GVRD, 2004) and a modest  
1927 enhancement of polychaete species known to be opportunistic in areas of organic enrichment.  
1928 These changes can be explained by increased organic loading alone, with no evidence of biotic  
1929 effects related to contaminants (Burd, 2003b). Certain contaminant inputs from the outfall are  
1930 discussed in more detail in Johannessen et al. (in press) and Macdonald et al. (in press).  
1931 Surrounding the impoverished zone is a region with less deposition of particulates that has no  
1932 notable biotic impoverishment and shows enrichment of some taxa. Echinoderms and  
1933 crustaceans, the taxa which are most impoverished in the maximum deposition zone, tend to  
1934 have enhanced abundance in this enrichment zone (Burd, 2003b; McPherson et al., 2007a).  
1935  
1936 To the south of the outfall, where no outfall particulates deposition can be detected, a range of  
1937 background biotic conditions provides context for the changes found within the two “effect”  
1938 zones. Interestingly, however, biotic impoverishment within this background area can be similar  
1939 to, or greater than, that found in the maximum deposition zone. This impoverishment does not  
1940 co-occur with organic enrichment, or any contaminant loading, but seems, rather, to be  
1941 characteristic of on-going and patchy physical disturbance of the sediment surface (Burd, 2003b,  
1942 McPherson et al., 2004b).  
1943  
1944 McPherson et al. (2007a) includes a time-scale comparison of biotic and geochemical conditions  
1945 which clearly show that both have remained relatively stable throughout the Iona outfall  
1946 monitoring region since 2000, including consistently low total organic carbon levels in sediments  
1947 throughout the monitoring grid, along with modest geochemical buildup of sulphides in the  
1948 maximum deposition zone. The reason for the uniformly low organic carbon levels is mostly the

1949 high loading of inorganic material from the south arm of the Fraser River, which tends to  
1950 continually bury the organic input, keeping the entire system in a relatively steady state.  
1951 However, rapid oxidation of carbon at this location (Wright et al., in press) from benthic  
1952 organisms may also contribute to the stable sediment conditions. In the maximum deposition  
1953 zone, infaunal biomass does not show any clear or consistent depression, but the community is  
1954 conspicuously devoid of echinoderms and infaunal amphipods (Burd, 2003b; McPherson et al.,  
1955 2007a).

1956

1957 In support of the monitoring program for the receiving environment of the Lions Gate  
1958 Wastewater Treatment Plant Outfall located at 1<sup>st</sup> Narrows (Fig. 1), the Greater Vancouver  
1959 Regional District has conducted annual biological monitoring in outer Burrard Inlet since 2002.  
1960 Prior to that, historical data from the Inlet had been collected by Environment Canada (c.f. Boyd  
1961 et al., 1998, and references therein) and the Department of Fisheries and Oceans (Burd and  
1962 Brinkhurst, 1990; Cross and Brinkhurst, 1991; Burd, 1992; Je et al., 2003). Although the earlier  
1963 work is not directly comparable to the GVRD monitoring due to differences in sampling  
1964 protocols, a comparative assessment of the historical biotic conditions and geochemical sediment  
1965 conditions of the outer Inlet was conducted by Burd (2004).

1966

1967 Both the deposition model of Hodgins et al. (2000) for the Lions Gate effluent solids and  
1968 analysis of cores taken in 2004 (Burd, 2004) suggest that some material from the outfall is  
1969 carried along the north shore of outer Burrard Inlet before settling offshore near the mouth of the  
1970 inlet (Fig. 1). The model predicts that the remaining material will go into the inlet, past 1<sup>st</sup>

1971 Narrows (Inner Burrard Inlet), under specific tidal conditions, although sediment sampling has  
1972 not confirmed this.

1973

1974 Unlike the receiving environment of the Iona Deep-Sea Outfall, where sediment chemistry and  
1975 biota clearly show identifiable changes which can be directly related to the deposition of  
1976 particulates from the outfall, no biotic changes which can be related to the discharge from the  
1977 Lions Gate Outfall have been detected (McPherson et al., 2007b). This is partially because the  
1978 outer Burrard Inlet is very well mixed and flushed (Thomson, 1981), and partially because there  
1979 are numerous sources of anthropogenic discharge into the water body which can cause  
1980 conflicting signals in sediment chemistry. Beyond First Narrows, the inner Inlet is particularly  
1981 prone to the conflicting signals due to the greater intensity and frequency of various urban and  
1982 industrial discharges than are found in the outer Inlet (GVRD, 2004). Sediment organic  
1983 enrichment accompanied by sporadic elevated levels of typical sewage indicators or tracers (i.e.  
1984 acid volatile sulphide, total organic carbon, sediment fecal coliforms, silver, 4-nonylphenol,  
1985 coprostanol) do occur along the north shore of the outer inlet (McPherson et al., 2007b), with  
1986 these effects decreasing with increasing distance offshore. Biotic changes in these areas have  
1987 been noted, but are minor (McPherson et al., 2007b).

1988

1989 One location in the Burrard Inlet monitoring program, beyond First Narrows (in the inner inlet),  
1990 has consistently shown more extreme organic enrichment and biotic impoverishment than any  
1991 location in the outer inlet. Despite this, sewage indicators (e.g., silver, 4-nonylphenol and  
1992 coprostanol) are not elevated, suggesting that sediment conditions are unlikely caused by the  
1993 Lions Gate Outfall. Instead, combined sewer overflows are a potential source of the organic



1994 enrichment which could be related to the biotic changes in the inner harbour (GVRD, 2004),  
1995 although multiple discharges in the area make it difficult to determine the source or sources.  
1996  
1997 A detailed analysis of sediment and outfall effluent metals data for 2002 and 2003 by Paine  
1998 (2003 q.v. GVRD, 2004) suggested that elevated levels of some metals in outer Burrard Inlet are  
1999 not likely related to the Lions Gate outfall, and are present at levels and in a form which should  
2000 be biologically unavailable. Other metals are present below levels expected to cause any  
2001 biological toxicity, based on Canadian Environmental Quality Guidelines (CCME, 1999).  
2002  
2003 Although technically not in the SoG, Victoria's Macaulay Point and Clover Point outfalls have  
2004 been extensively studied and the long-term data on the benthos provide important context for  
2005 similar habitats in the SoG. Also, despite the fact that the depth and current regime trap the  
2006 plumes, suggesting that material from these outfalls is not likely to enter the SoG, there are times  
2007 when the plumes have been known to surface so that any dissolved organics or contaminants in  
2008 the upper water layer could enter through Haro Strait and eventually find their way to sediments  
2009 in the SoG (Thomson, 1981) (also see Section 1.2). For that reason, information about the  
2010 benthos near these two outfall areas is covered briefly below.  
2011  
2012 Victoria's Macaulay Point is an area of sandy substrate and high current that receives only  
2013 screened (i.e. primary treatment) wastewater that is discharged at an approximate mean depth of  
2014 60-65 m. The Clover Point outfall in Victoria discharges at a similar depth but into a rocky,  
2015 cobble environment that is dominated by a horse mussel (*Tressus tapyx*) community (Capital  
2016 Regional District, 2000). Environmental monitoring of the benthic receiving environment at

2017 both of these major Victoria outfalls has been conducted since the early 1970s (Balch et al.,  
2018 1973; 1975), with a revision of methods and quality control initiated in 2000  
2019 ([http://www.crd.bc.ca/es/environmental\\_programs/wastewater\\_marine/macaulay/reports.htm](http://www.crd.bc.ca/es/environmental_programs/wastewater_marine/macaulay/reports.htm)).  
2020 Numerous reports have been prepared by consultants on the results of this monitoring, along  
2021 with annual monitoring reports (Capital Regional District, 2003, 2004, 2005; Paine, Ledge and  
2022 Associates, 2004), along with a recent review of the Liquid Waste Management Plan and  
2023 seafloor triggers by Stubblefield et al. (2006). Burd (2003c) reviewed the 1994 to 2001 data on  
2024 benthic infauna and sediment geochemistry from the Macaulay Point outfall area and reported  
2025 that the monitoring data show some faunal effects, but severe biotic degradation is not occurring  
2026 in the vicinity of this outfall. Although, based on the available data, it is impossible to determine  
2027 what toxic contamination effects may be important to the fauna of the receiving environment, the  
2028 patterns of faunal change relative to the outfall strongly suggest that sediment geochemical  
2029 changes and particle size are the predominant factors affecting faunal composition (Burd,  
2030 2003c). The sampling stations are situated radially around the outfall along a spatial gradient to  
2031 800m distant, with diminishing biotic and geochemical impacts to this distance in the E and SE  
2032 (Burd, 2003c).

2033  
2034 The biotic monitoring at the Clover Point outfall consists entirely of growth and condition factors  
2035 for the dominant species, horse mussels. The hard substrates in this environment do not lend  
2036 themselves to sediment sampling. Historically, the mussels within 800 m of the outfall tend to  
2037 show a declining gradient of enhanced growth compared with reference locations  
2038 ([www.crd.bc.ca/wastewater/marine/reports.htm](http://www.crd.bc.ca/wastewater/marine/reports.htm)).

2039

### 2040 3.2 Ocean Disposal Sites

2041 There are 11 designated ocean disposal sites regulated by Environment Canada in the SoG.  
2042 Locations and annual dumping volumes for these sites are available at the Environment Canada  
2043 website ([http://www.pyr.ec.gc.ca/disposal\\_at\\_sea/sitemap\\_e.htm](http://www.pyr.ec.gc.ca/disposal_at_sea/sitemap_e.htm)). The site also contains links to  
2044 monitoring reports for all the sites over time. A brief overview of ocean dumping in BC is given  
2045 in Ellis (1982), but there is almost no biological monitoring data from dumpsites in the SoG,  
2046 except for the Point Grey dumpsite. Side-scan mosaicing has been proposed as an efficient  
2047 method of monitoring new debris accumulation and dispersal at ocean disposal sites (Mosher et  
2048 al., 1997).

2049 The Point Grey disposal site, outside Burrard Inlet on the southeast side of the Strait, is the  
2050 largest multi-user site in BC. This site has been in continuous use since the 1930s, and has been  
2051 regulated by Environment Canada since 1975. Wilson and McKinnon (2003) reviewed the  
2052 history, sediment and benthos monitoring data gathered for the Point Grey site from 1975 through  
2053 2001. The site is between 230 and 250 m deep, with 80% of the sedimenting material from  
2054 dumping and most of the remainder from the Fraser River discharge. In the late 1970s there was  
2055 clear evidence of material from Burrard Inlet dumped outside of, *en route* to, the disposal site  
2056 and evidence of this trail was still present in the early 1990s (see Mosher et al., 1997 and  
2057 [www.gsc.nrcan.gc.ca/marine/\\_gbgi/proj\\_ptgrey\\_e.php](http://www.gsc.nrcan.gc.ca/marine/_gbgi/proj_ptgrey_e.php)). In addition, detailed investigation of  
2058 polycyclic aromatic hydrocarbon (PAH) signatures based on area-wide data suggested that  
2059 recently dumped contaminants from Burrard Inlet were evident at the north end of the Iona  
2060 outfall monitoring transect (80 m depth) in 2000 (Yunker, 2000; Yunker et al., 2000), well  
2061 outside the ocean disposal boundaries.

2062 Benthic infaunal surveys were conducted periodically at the Point Grey disposal site (most  
2063 recently in 1994) but sampling effort and taxonomic work varied considerably (Wilson and  
2064 McKinnon, 2003). The accumulated material is presently significantly coarser than the  
2065 surrounding area, probably due to winnowing and transport on the way to the bottom. Despite  
2066 the limitations to interpretation imposed by taxonomic effort and quality control, and  
2067 modification of substrates within the dumpsite, Wilson and McKinnon (2003) concluded that the  
2068 Environment Canada monitoring data on benthic invertebrate biota did not show notable  
2069 differences from biota found outside the dumpsite; for a guideline, the authors used the range in  
2070 values expected within reference conditions for the Benthic Response Index (BRI) from the  
2071 Southern California Coastal Water Research Project (SCCWRP). Unfortunately the BRI is  
2072 based on local species-specific data, whereas the Point Grey biotic data were for different species  
2073 identified only to the family level or higher, thus making extrapolation to the BRI problematic.  
2074 Probably more convincing is the fact that on-going visual surveys (see below) show that the  
2075 disposal site has historically been dominated by a range of polychaete taxa and had numerous  
2076 burrowing and near-surface, echinoderms and amphipods, both of which groups are known to be  
2077 sensitive to contamination and organic enrichment, as well as unusually high sedimentation  
2078 (Burd, 2003b).

2079 At the Point Grey disposal site, ROVs equipped with video and still cameras are used  
2080 periodically to record images of the disposal site and the surrounding ocean floor (Wilson and  
2081 McKinnon, 2003). Predetermined track lines plotted across the disposal site are followed by the  
2082 ROV and continuous images of the ocean bottom are recorded. These visual images aid in the  
2083 qualitative evaluation of the disposal site environment. ROV surveys show that the dumping of  
2084 debris (e.g. logs, wire and construction materials) has created a more heterogeneous habitat than

2085 would normally be present at this depth, resulting in an artificially increased biodiversity of hard  
2086 and soft substrate fauna.

2087

### 2088 **3. 3 Pulp and Paper Mills**

2089 Macdonald et al. (1991) concluded that the pulp and paper mills in the SoG and surrounding  
2090 fjords were contributing significantly to organic carbon input into the sediments of the Strait.  
2091 Since then, the draft Pulp and Paper Effluent Regulations (PPER) were promulgated by  
2092 Environment Canada in 1992, put into effect in 1996 and revised in 2004 (Regulations  
2093 Amending the Pulp and Paper Effluent Regulations, (RAPPER), in order to reduce and control  
2094 emissions (<http://www.ec.gc.ca/nopp/pandp/en/p2004Letter.cfm>). There are 6 operating pulp  
2095 and paper mills which discharge effluent into marine subtidal habitats in the SoG and which are  
2096 regulated by Environment Canada under the PPER. The mills in the Strait are shown in Fig. 1  
2097 (Crofton, Harmac, Elk Falls, Powell River and two in Howe Sound). Monitoring takes place  
2098 from 30 m to 135 m depth and all but one of the mills discharge primarily into soft substrates  
2099 ranging from 98% sand to 98% silt/clay ([http://www.ec.gc.ca/EEM/English/PulpPaper](http://www.ec.gc.ca/EEM/English/PulpPaper/general.cfm)  
2100 [/general.cfm](http://www.ec.gc.ca/EEM/English/PulpPaper/general.cfm)). The Elk Falls mill discharges onto hard substrates and the Environmental Effects  
2101 Monitoring (EEM) program for that mill focuses on invertebrate communities found in intertidal  
2102 *Fucus* beds ([www.ec.gc.ca/eem/English/PulpPaper/](http://www.ec.gc.ca/eem/English/PulpPaper/data/showinfo.cfm?Mill_id=PP1122)  
2103 [data/showinfo.cfm?Mill\\_id=PP1122](http://www.ec.gc.ca/eem/English/PulpPaper/data/showinfo.cfm?Mill_id=PP1122)).  
2104 The current Environmental Effects Monitoring (EEM) program for the pulp and paper mills has  
2105 now completed 3 cycles: 1996, 2000 and 2004. Data collection for cycle 4 is complete and  
2106 reports have been submitted to Environment Canada but are not yet publicly available. The EEM  
2107 program and technical guidance for monitoring are available at <http://www.ec.gc.ca/EEM/>

2108 [English/PulpPaper/general.cfm](#), including the national database of benthic infauna and habitat  
2109 conditions.

2110  
2111 Results from Environment Canada's national synthesis reports available on the website show that  
2112 although effluent quality from pulp and paper mills has vastly improved since initiation of the  
2113 PPER (following the EEM cycle 1), effects on benthic invertebrates and fish are still observed.  
2114 Some pulp and paper mill reports suggest that current effects on marine benthos are still related  
2115 to historical deposition and that current inputs are much less of a problem. Aside from organic  
2116 enrichment, the accumulation of wood fibre mats, organochlorines and dioxins/furans have been  
2117 historical problems. Although the organic contaminants mentioned are now controlled (or  
2118 banned) substances, their historical presence in these sediments suggests that they are still  
2119 cycling through the food chain in the vicinity of pulp and paper mills.

2120  
2121 The aforementioned synthesis reports further suggest that while eutrophication of the water  
2122 column is the dominant factor affecting freshwater benthos exposed to pulp and paper mill  
2123 effluent input, the typical response of biota in marine/estuarine benthic habitats is a decrease in  
2124 abundance and richness of taxa that is more indicative of toxic, or smothering, effects  
2125 (<http://www.ec.gc.ca/EEM/English/PulpPaper/general.cfm>). Near mill discharges, elevated C/N  
2126 ratios (>15) are common while sediment sulphides are not particularly elevated in comparison,  
2127 for example, with fish farm sediments (Burd, 2006). However, a re-examination of the EEM  
2128 cycle 3 data from the SoG shows no trends in species richness or abundance related to distance  
2129 from the discharge, sediment redox, sulphides, TOC or C/N ratio (Burd, unpublished data).

2130 However, there is some indication that taxa number and abundance decline with increasing  
2131 depth, as found overall in the SOG data (Burd et al. in press; see Section 2).

2132

2133 Although the pulp and paper mills in the SoG appear to have no gross impact on subtidal  
2134 infaunal benthos, this should not be interpreted to mean that the mills are not affecting the  
2135 benthos; for example, quality control has never been standardized for the taxonomy of the pulp  
2136 and paper mills marine EEM (technical guidance document  
2137 <http://www.ec.gc.ca/EEM/English/PulpPaper/general.cfm>).

2138

2139 Environment Canada's EEM program for pulp and paper mills includes one mill site in the SOG  
2140 which is predominantly hard substrate and is thus not amenable to the regular infaunal sampling  
2141 methods recommended in the technical guidance. Data from the Elk Falls mill includes mixed  
2142 studies of *Fucus* recolonization baskets in some cycles and standard beach quadrat surveys in  
2143 others. The recolonization studies show a limited (rapid colonizing) species list of amphipods,  
2144 isopods, and nemertean that is missing the typical hard substrate species such as the molluscs  
2145 and polychaetes, and larger predators ([http://www.ec.gc.ca/eem/English/PulpPaper/data/  
2146 showinfo.cfm?Mill\\_id=PP1122](http://www.ec.gc.ca/eem/English/PulpPaper/data/showinfo.cfm?Mill_id=PP1122)). The quadrat studies provide a species list much more typical  
2147 of *Fucus* habitats as described in the Shorekeepers lists ([http://www.shim.bc.ca/atlas/sk/  
2148 main.htm](http://www.shim.bc.ca/atlas/sk/main.htm)). At present, these studies have not shown any gradient responses in biota to distance  
2149 from the discharge. Based on research in the SoG, Bard (1998) describes biotic sensitivities and  
2150 a proposed biotic index related to intertidal rocky beach fauna in areas affected by pulp mill  
2151 effluent in BC.

2152 High organic loading from pulp mills and log boom areas is relatively refractory due to the slow  
2153 rate of bacterial and invertebrate breakdown of organics. Therefore, the packing of dense debris  
2154 typically causes severe sediment deoxygenation without dramatically elevated sulphides in  
2155 sediments (<http://www.ec.gc.ca/eem/english/PulpPaper/default.cfm>; Samis et al., 1999). These  
2156 areas may show a generalized depression of fauna (see Burd et al, in press), but be patchy,  
2157 depending on deposition characteristics. The benthos may take a long time to recover in  
2158 sediments with heavy wood-fibre mats due to the reduced and slow biotic activity, and  
2159 sometimes low penetrability by burrowers.

#### 2160 **3. 4 Log Booms**

2161 Areas of near-shore log booms are common along the SoG coastline. Log storage activities  
2162 primarily impact low intertidal and shallow subtidal habitats within estuaries. Impacts include  
2163 the physical shading of habitat by booms, leading to decreased primary productivity by algae and  
2164 eelgrass (NEMP, 2002). At low tide, the physical grounding and abrasion by log booms result in  
2165 compaction of sediments, scouring and physical disruption of habitats, particularly eelgrass beds  
2166 (NEMP, 2002). Adjacent intertidal areas can be similarly impacted by escaped logs and  
2167 propeller wash from tow boats can scour and increase the levels of suspended sediment in the  
2168 water column (NEMP, 2002).

2169  
2170 The working of logs against each other within the bundle results in deposition and accumulation  
2171 of bark and wood debris on bottom sediments. These deposits are relatively refractory and the  
2172 slow rate of bacterial and invertebrate breakdown can cause long-term stress to the benthic  
2173 environment as a result of sediment deoxygenation, although sulphide levels are not dramatically



2174 elevated (<http://www.ec.gc.ca/eem/english/PulpPaper/default.cfm>). General biotic effects may  
2175 be similar to those described for pulp and paper receiving environments (Section 3.3), although  
2176 the deposition of wood debris tends to be coarser and may be much heavier under log booms.  
2177 McGreer et al. (1984) examined the recovery of an intertidal community in an area of the  
2178 Nanaimo River estuary from which log booms had been removed. At 13 months after removal,  
2179 common macro-invertebrate species were those typical of organic enrichment but the overall  
2180 abundance was lower than that of the control area. The reduction in abundance was attributed to  
2181 a shallow, but persistent, redox boundary at the log removal site. The effects of wood waste on  
2182 near-shore sand beds (4-11 m) and associated fauna were studied by Conlan (1977) and Conlan  
2183 and Ellis (1979), who found that deposition of >1 cm of wood debris caused notable faunal  
2184 impoverishments, particularly in the suspension feeding fauna. Additional studies have suggested  
2185 that wood debris may also inhibit the abundance of some infaunal bivalves (Burd et al., in press;  
2186 Kathman et al., 1984; <http://www.mareco.org/report/intro.htm>). Kathman et al. (1984) examined  
2187 the recolonization of settling trays in 15-20 m depth in outer Burrard Inlet, using different  
2188 concentrations of wood waste from the Port Mellon pulp mill location in Howe Sound. After 11  
2189 weeks, they found that the 20% wood waste trays had a higher species diversity and lower  
2190 dominance than found in the 0%, 50% and 100% wood waste trays, whereas abundance was  
2191 equally high in the 20% and 100% trays. However, the 100% trays were dominated by  
2192 nematodes, typical organic enrichment polychaetes and the wood-burrowing bivalve *Bankia*  
2193 *setacea*. Other bivalves and polychaetes were abundant in the 0% and 20% trays, but rare in the  
2194 50% and 100% trays.

2195

2196 A larger-scale examination of benthic responses to log-boom operations for the north coast of  
2197 British Columbia, as well as Esquimalt Harbour (Victoria) is underway as part of a Ph.D. project  
2198 ([http://www.erf.org/cgi-bin/conference\\_abstract.pl?conference=erf2003%id+755](http://www.erf.org/cgi-bin/conference_abstract.pl?conference=erf2003%id+755)).

2199

### 2200 **3.5. Mine Tailings and Acid Mine Drainage**

2201 Between 1902 and 1974, the Britannia copper/zinc mine discharged 40 million tonnes of tailings  
2202 into Howe Sound. Tailings were concentrated on the slope within 3 km of Britannia Beach but  
2203 also covered most of the floor of the Sound's inner basin. During mine operations, subtidal  
2204 sediments in areas deeper than 30 m had levels of copper and zinc that were considerably  
2205 elevated above background (Levings and McDaniel, 1973, 1976; McDaniel, 1973), as well as  
2206 above the current Probable Effects Levels for marine sediments (CCME, 1999). They also found  
2207 that burial by the Squamish River sediment load and inputs from local creeks had diluted, or  
2208 covered, the deposited tailings and reduced the metal concentration in surface sediments. Below  
2209 sill depth (73 m), waters in Howe Sound tend to be seasonally anoxic, limiting not only the  
2210 mobility of metals from the sediments but also the biodiversity and abundance of benthic fauna,  
2211 regardless of tailings (Levings et al., 1983). Several studies in the 1970s focused on the effects  
2212 of deposition of metals and tailings from the active Britannia Mine operation on the  
2213 macrobenthos (Levings and McDaniel, 1973; McDaniel, 1973; Levings and McDaniel, 1976),  
2214 but based on more recent studies near Britannia (Ellis and Hoover, 1990) and on long-term  
2215 recovery of sediments affected by tailings from mines located outside the SoG in British  
2216 Columbia (Burd et al., 2000b; Burd, 2002), it is assumed that the deep benthos has recovered  
2217 some 30 years after cessation of tailings deposition. However, it is also clear that considerable  
2218 acid mine drainage is still leaching out into the near shore area around the historical Britannia

2219 mine. Recent studies confirm impacts on near shore fish and fish habitat (for an overview, see  
2220 Hagan et al., 2004). In addition, Grout and Levings (2001) examined the effects of acid mine  
2221 drainage on intertidal mussels in the area and showed that caged and ambient mussels were  
2222 adversely affected by elevated tissue copper levels to a distance of about 2 km N and S of the  
2223 discharge creek. In December 2001, the acid mine drainage was diverted to an outfall at 30 m  
2224 depth into Howe Sound. Zis et al. (2004) looked at the intertidal community recovery at  
2225 Britannia Beach after diversion, and found that some, but not total recovery was evident in  
2226 invertebrate species number and abundance, as well as transplanted mussels. The authors  
2227 concluded that some continued seepage from the old mine was still inhibiting normal growth and  
2228 survival in the intertidal area. G3 Consulting (2003) provided a report on the shallow subtidal  
2229 (<30 m depth) biota, sediment metals and organics from the foreshore around the Britannia mine.  
2230 Levings et al. (2004) describe the toxicity of the acid mine drainage to estuarine organisms from  
2231 the discharge creek, noting that invertebrate food resources for juvenile salmonids in the  
2232 intertidal near the drainage creek were adversely affected by the acid mine drainage.

### 2233 **3.6 Aquaculture**

2234 In BC, the majority of the finfish aquaculture industry in the inside waters is located north of the  
2235 SoG; there are only a few salmonid farms at the south end of Johnson Strait (the north end of the  
2236 SoG) and in some of the contiguous mainland fjords. Where organic deposition is excessive, and  
2237 fauna have declined, reactive organic detritus may be present in a labile state as a flocculent  
2238 layer on the sediment surface (Kristensen, 1988). Fish farms provide an example of an organic  
2239 source with minor copper (antifoulants) and zinc (feed) contaminants (c.f. Brooks 2001). Studies  
2240 of benthic faunal patterns and recovery at the few marine mine tailings deposition sites,

2241 however, suggest that particulate levels of these metals typically found under fish farms do not  
2242 seem to have a notable effect on infaunal benthos in the deeper subtidal, despite the fact that  
2243 bivalves, in particular, can accumulate metals (Burd et al., 2000b; Burd, 2002). Rather, zinc and  
2244 copper levels are typically used as deposition tracers around fish farms (Yeats, 2002).

2245 The organic deposition in the vicinity of fish farms tends to be highly labile, as compared to  
2246 wood fibre waste or other organic materials. Hence, the organic material tends to be broken  
2247 down relatively quickly (e.g. in comparison to wood fibre debris) and recovery proceeds at a  
2248 measurable pace. The effects of this highly labile deposition include sediment de-oxygenation  
2249 and hydrogen sulphide accumulation which lead to the enrichment of some taxa such as the  
2250 opportunistic polychaete *Capitella capitata* complex that are tolerant of these conditions and the  
2251 impoverishment of sensitive taxa. At fish farms where organic enrichment loads are high and  
2252 sediment geochemistry includes low oxygen levels and high sulfide accumulation (i.e. ~6000  
2253  $\mu\text{m}$ ), tolerant and opportunistic polychaete species tend to dominate on soft substrates and on  
2254 hard substrates where sedimentation occurs, whereas most other fauna disappear under these  
2255 extreme conditions (Brooks, 2001; Burd, 2006; Hargrave et al., 2008). However, some epifaunal  
2256 crustaceans typically found in detritus mats nearshore may thrive in the debris mats under the net  
2257 cages (Burd, 2006).

2258 Under more moderate sulphide buildup conditions (1700-3000  $\mu\text{M}$ ), a variety of organism types  
2259 may be present, but Burd (2006) show that some biotic impoverishments are highly likely, along  
2260 with a potential proliferation of opportunistic polychaetes. In particular, echinoderms and  
2261 infaunal crustaceans appear to be highly sensitive to organic enrichment conditions in sediments  
2262 (Burd, 2006; McPherson et al., 2007a). On hard substrates, some cnidarians (such as *Metridium*

2263 *senile*) may be opportunistic under moderate organic enrichment conditions, but echinoderms  
2264 will still be absent, as will larger sponges (Emmett et al., 2005; 2006; 2007), due primarily to  
2265 excessive deposition, and/or near-bottom low oxygen conditions. Where organic loading is  
2266 elevated, but within the assimilative capacity of the sediments, a biotically-enriched community  
2267 may be present (Burd, 2006; Brooks, 2001). Recent reviews of biotic effects related to fish farms  
2268 in BC are given in Brooks (2001), Burd (2003a; 2006) and Hargrave et al. (2008). Some  
2269 important information on general sediment sulphide tolerance of common BC species is  
2270 available in Brooks (2001).

2271 A large number of beach and near-shore shellfish aquaculture sites are located in Baynes Sound  
2272 on the east coast of Vancouver Island. Carswell et al. (2006) describe an aerial survey method  
2273 that has been used to show that >20% of the intertidal zone of the sound is occupied by shellfish  
2274 tenures. A review of the available literature and monitoring data related to potential impacts from  
2275 shellfish culture for the intertidal areas of Baynes Sound is given in Jamieson et al. (2001). To  
2276 date, studies show that the benthic impact of deep-water suspended culture of Pacific oysters  
2277 appears to vary depending on the specifics of the site, including hydrography, bathymetry and  
2278 natural deposition rates and sediment characteristics (Barnes, 2006). Regardless, data revealed  
2279 that the benthic invertebrate communities in close proximity to the shellfish farms showed no  
2280 reduction in either faunal abundance or diversity (Barnes, 2006). In Baynes Sound, an area of  
2281 the SoG heavily tenured by shellfish leases, Bendell-Young (2006) studied three geographically  
2282 similar clam farm beach sites, along a farming intensity gradient (fallow, 3 years active, 5 years  
2283 active). In contrast to the fallow site, the 3 and 5 year active sites had intertidal regions with  
2284 heavier silt and organic matter, lower species richness and increased domination by bivalves.  
2285 However, a geographically more diverse study, including a site on the west coast of Vancouver

2286 Island, found that clam density on netted farm sites was significantly greater than on reference  
2287 sites only in the low intertidal and that this significant increase in total clam density mirrored the  
2288 increase in 1 species of bivalve, *Venerupis philippinarum*, in this stratum at farm sites (Whiteley  
2289 and Bendell-Young, 2007). The study also demonstrated that bivalve species composition was  
2290 not significantly different between farms and reference sites, suggesting that predator nets did  
2291 not effectively change the structure of the infaunal communities at these sites. Farm sites were  
2292 more similar to each other as a group than reference sites, however, and the authors suggest that  
2293 this may lead to a loss of the regional distinctness that was evident among the reference sites  
2294 (Whiteley and Bendell-Young, 2007).

### 2295 **3.7 Bottom Trawling**

2296 In near-shore coastal areas such as the SoG, bottom trawling is likely to result in physical  
2297 disturbance. Bottom trawling can have devastating effects on bottom infaunal and epifaunal  
2298 communities in other coastal areas (Watling and Norse, 1998). For example, otter trawling on  
2299 soft bottoms has been found to significantly reduce the abundance of most invertebrate taxa  
2300 (Engel and Kvitek, 1998; and other papers in Conservation Biology issue 12: Vol. 6). Effects on  
2301 the benthos range from crushing, burying and dislocation of fauna, to habitat destruction and  
2302 resuspension of fine particulates into a turbid boundary layer. Such practices can also damage  
2303 nursery grounds or bottom fish stock. Various studies report a reduction in organism abundance  
2304 and species richness  $\geq 50\%$ , and substantial reductions in biomass (for review, see Watling and  
2305 Norse, 1998). The effects of bottom trawling do not resemble any of the contaminant impacts  
2306 described in the literature (Burd 2003b; Cook et al., in press), and arguments have been made  
2307 that certain refugia such as the sponge reefs in the Strait should be protected from bottom

2308 trawling (Conway et al., 2007). Unfortunately, there is virtually no concurrent spatial or temporal  
2309 information on the combined, or synergistic, biotic effects of contaminant discharges and bottom  
2310 trawling in the SoG.

### 2311 **3.8 General Contaminants Loadings (non-point source)**

2312 There are numerous sources of contaminants entering the SoG, particularly originating from, or  
2313 as a result of, the highly urbanized centers near the BC/Washington border. Aside from  
2314 localized surveys of sediment contaminant loadings related to specific discharges (see references  
2315 in above sections 3.1 to 3.7 related to monitoring programs for site-specific discharges), there  
2316 have been a few broader-scale studies of certain contaminants of concern or tracers of discharge  
2317 types, focusing on their distributions and budgets (c.f. Macdonald et al., 1991,1992 – Pulp mills;  
2318 Gordon,1997 – silver; Shang et al., 1999 – nonylphenols; Yunker et al., 1999 – PAHs;  
2319 Johannessen et al. 2005a – Mercury; Johannessen et al. in press – PCBs/PBDEs). In addition,  
2320 the potential for development of bottom water and sediment hypoxia from organic loading have  
2321 been discussed using organic carbon budgets (Johannessen et al., 2003), and evaluation of  
2322 sediment organic/oxygen conditions based on redox chemicals in cores (Macdonald et al., in  
2323 press).

2324 Sediment guidelines and all the studies that have contributed to their development (CCME, 1999;  
2325 BCWQO;[http://www.env.gov.bc.ca/wat/wq/BCguidelines/approv\\_wq\\_guide/approved.html](http://www.env.gov.bc.ca/wat/wq/BCguidelines/approv_wq_guide/approved.html))  
2326 provide some guidance related to possible responses of benthic invertebrate fauna to  
2327 contaminants of concern. However, field validation of these hypothetical tolerances and  
2328 responses is lacking for SoG fauna.

#### 2329 **4. Conclusions**

2330 Although there is considerable descriptive information pertaining to invertebrate benthos (largely  
2331 unpublished) of the SoG, quantitative evaluations are much less abundant and patchy spatially  
2332 and temporally. Burd et al. (in press) provide a comparative assessment of infaunal biomass,  
2333 species richness, and abundance measures which can be reasonably predicted by measurements  
2334 of organic quality and flux to sediments in the SoG. Results are also dependent on the source and  
2335 relative quantity of inorganic flux, with areas influenced by the Fraser River discharge providing  
2336 apparently more productive substrate for macro-invertebrates than marine depositions. With a  
2337 broader scale understanding of sediment organic and inorganic sources and fluxes in the SoG, it  
2338 may be possible to begin to model and ground-truth subtidal benthic productivity of the SoG.  
2339 This would also require a clearer understanding of how the smaller invertebrate groups  
2340 (meiofauna) and microfauna respond to sediment organic and inorganic fluxes. The next logical  
2341 step would be to interpret sediment productivity in the context of budgets/models of sediment  
2342 contaminants, organic inputs and redox conditions for the SoG. In addition to understanding how  
2343 benthic organisms may be affected by contaminant and organic loading on a regional scale, the  
2344 potential for bio-accumulation and trophic transfer of contaminants of concern needs to be  
2345 studied for the bottom-dwelling portion of the subtidal food chain. Predicting the effects of on-  
2346 going climate changes will also require an understanding of how the sessile components of the  
2347 benthic ecosystem are likely to change in response to major sedimentation shifts or events.

2348

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2350



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2356 Resources Canada.

2357

2358

2359

2360

ACCEPTED MANUSCRIPT

2361 **6.0 References**

2362

2363 2WE Consulting, 1999. Iona Deep-sea Outfall 1998 Environmental Monitoring Program, Post-  
2364 discharge Review, Report for Greater Vancouver Regional District by 2WE Associates  
2365 Consulting Ltd., Victoria, B.C., 97 pp.

2366 Albright, L.J., 1983. Influence of river-ocean plumes upon bacterioplankton production of the  
2367 Strait of Georgia, British Columbia. Marine Ecology Progress Series 12, 107-113.

2368 Anderson, J.J., Devol, A.H., 1973. Deep water renewal in Saanich Inlet, an intermittently anoxic  
2369 basin. Estuarine, Coastal and Shelf Science 1, 1-10.

2370 Archipelago Marine Research Ltd., 2000. Subtidal video (SIMS) survey of the Manley Creek  
2371 landfall site at Boatswain Bank, British Columbia. Report to the Georgia Strait Pipeline  
2372 Crossing Ltd.

2373 Asmus, H. 1987. Secondary production of an intertidal mussel bed community related to its  
2374 storage and turnover compartments. Mar. Ecol. Prog. Ser. 39, 251-256.

2375 BC Ministry of Environment Lands and Parks, 1996. Saanich Inlet Study. Synthesis Report  
2376 Summary, 35 pp.

2377 Baba, K., 1983. *Spongicoloides hawaiiensis*, a new genus of shrimp (Decapoda: Stenopodidea)  
2378 from the Hawaiian Islands. Journal of Crustacean Biology 3, 477-481.

2379 Bailey, H.C., McPherson, C.A., Hodgins, D.O., Fanning, L., Paine, M.D., Burd, B.J.,  
2380 Macdonald, V., Brooks, G.C., Chen, F., Brand, D., Raverty, S., 2003. Iona Deep-Sea  
2381 Outfall, 2001 Environmental Monitoring Program. Final Report, Prepared for the Greater  
2382 Vancouver Regional District by EVS Environmental Consultants Ltd., North Vancouver  
2383 BC, 344 pp. + appendices.

- 2384 Balch, N., Brown, D., Pym, R., Marles, E., Ellis, D.V., Littlepage, J., 1975. Monitoring marine  
2385 outfalls by using ultraviolet absorbance. *Journal of the Pollution Control Federation*, 47,  
2386 195-202.
- 2387 Balch, N., Ellis, D.V., Littlepage, J., 1973. Macaulay Point outfall monitoring programme, May  
2388 1970 – October 1972, Volume 1 and 2 final report to Capital Regional District, Victoria,  
2389 BC by Department of Biology, University of Victoria.
- 2390 Bard, S.M., 1998. A biological index to predict pulp mill pollution levels. *Water Environment*  
2391 *Research* 70, 108-122.
- 2392 Barnes, P.A.G., 1987. Aspects of the Ecology of the Gutless Protobranch Bivalve, *Solemya reidi*.  
2393 University of Victoria, M.Sc. thesis, 435 pp.
- 2394 Barnes, P.A.G., 2006. Shellfish Culture and Particulate Matter Production and Cycling: A  
2395 Literature Review, B.C. Aquaculture Research and Development Committee. Project  
2396 AE02.03-02.01, 101 pp.
- 2397 Barthel, D., 1992. Do hexactinellids structure Antarctic sponge associations? *Ophelia* 36, 111-  
2398 118.
- 2399 Bell, J.J., Barnes, D.K., 2000a. The distribution and prevalence of sponges in relation to  
2400 environmental gradients within a temperate sea lough: vertical cliff surfaces. *Diversity*  
2401 *and Distributions* 6, 283-303.
- 2402 Bell, J.J., Barnes, D.K., 2000b. The distribution and prevalence of sponges in relation to  
2403 environmental gradients within a temperate sea lough: inclined cliff surfaces. *Diversity*  
2404 *and Distributions* 6, 305-323.

- 2405 Bendell-Young, L.I., 2006. Contrasting the community structure and select geochemical  
2406 characteristics of three intertidal regions to shellfish farming. *Environmental*  
2407 *Conservation* 33, 21-27.
- 2408 Berggren, M., 1993. *Spongiocaris hexactinellicola*, a new species of stenopodidean shrimp  
2409 (Decapoda: Stenopodidae) associated with hexactinellid sponges from Tartar Bank,  
2410 Bahamas. *Journal of Crustacean Biology* 13, 784-792.
- 2411 Bernard, F.R., 1978. British Columbia Faunistic Survey: Subtidal and Deep-water Megafauna of  
2412 the Strait of Georgia. Canadian Fisheries and Marine Services Manuscript Report 1488,  
2413 41 pp.
- 2414 Bett, B.J., Rice, A.L., 1992. The influence of hexactinellid sponge (*Pheronema carpenteri*)  
2415 spicules on the patchy distribution of macrobenthos in the Porcupine Seabight (bathyal  
2416 NE Atlantic). *Ophelia* 36, 217-226.
- 2417 Boatman, D.C., Murray, J.W., 1982. Modeling exchangeable  $\text{NH}_4^+$  adsorption in marine  
2418 sediments: Process and controls of adsorption. *Limnology and Oceanography* 27, 99-110.
- 2419 Bornhold, B.D., 1978. Carbon/nitrogen (C/N) ratios in surficial marine sediments of British  
2420 Columbia, in: Current Research, Part C, Geological Survey of Canada, Scientific and  
2421 Technical Notes, Paper 78-1C, 108-112.
- 2422 Bornhold, B.D., Harper, J.R., 2002. Pilot Nearshore Habitat Mapping Using Acoustic and Visual  
2423 Techniques, Report Prepared for the North Pacific Research Board Anchorage, Alaska,  
2424 (Project R0201), 128 pp.
- 2425 Bornhold, B.D., Ren, P., Prior, D.B., 1994. High-frequency turbidity currents in British  
2426 Columbia fjords. *Geo-Marine Letters* 14, 238-243.

- 2427 Bousfield, E.L., 1957. Ecological investigations of shore invertebrates of the Pacific coast of  
2428 Canada. National Museum of Canada Bulletin 147, 105-155.
- 2429 Boyd, J., Baumann, J., Hutton, K., Bertold, S., Moore, B., 1998. Sediment Quality in Burrard  
2430 Inlet Using Various Chemical and Biological Benchmarks, Burrard Inlet Environmental  
2431 Action Program, Burnaby, British Columbia, 87 pp. + appendices.
- 2432 Brenchley, G.A., 1982. Mechanisms of spatial competition in marine soft-bottom communities.  
2433 Journal of Experimental Marine Biology and Ecology 60, 17-33.
- 2434 Brinkhurst, R.O., 1987. Distribution and Abundance of Macrobenthic Fauna from the  
2435 Continental Shelf off Southwestern Vancouver Island, British Columbia. Canadian  
2436 Technical Report on Hydrography and Ocean Sciences 89, 45 pp.
- 2437 Brinkhurst, R.O., Casillas, E., Word, J.Q., 1994. Marine benthos of British  
2438 Columbia/Washington State boundary waters, in: Wilson, R.C.H., Beamish, R.J.,  
2439 Aitkens, F., Bell, J., (Eds.), Review of the Marine Environment and Biota of Strait of  
2440 Georgia, Puget Sound and Juan de Fuca Strait. Canadian Technical Report of Fisheries  
2441 and Aquatic Sciences 1948, 187-202.
- 2442 Brooks, K.M., 2001. An evaluation of the relationship between salmon farm biomass, organic  
2443 inputs to sediments, physiochemical changes associated with those inputs and the  
2444 infaunal response-with emphasis on total sediment sulfides, total volatile solids, and  
2445 oxidation reduction potential as surrogate endpoints for biological monitoring, Technical  
2446 Advisory Group, Ministry of Environment, Lands, and Parks, Port Townsend,  
2447 Washington, 172 pp. + appendices.

- 2448 Bruce, A.J., Baba, K., 1973. *Spongiocaris*, a new genus of stenopodidean shrimp from New  
2449 Zealand and South Africa waters, with a description of two new species (Decapoda:  
2450 Nutantia, Stenopodidea). *Crustaceana (Leiden)* 25, 153-170.
- 2451 Burd, B.J., 1985. Respiration of a low oxygen tolerant galatheid crab, *Munida quadrispina*  
2452 (Benedict, 1902). *Canadian Journal of Zoology* 63, 2538-2542.
- 2453 Burd, B.J., 1988. Comparative gill characteristics of *Munida quadrispina* (Decapods,  
2454 Galatheidae) from different habitat oxygen conditions. *Canadian Journal of Zoology* 66,  
2455 2320-2323.
- 2456 Burd, B.J., 1992. Qualitative and quantitative studies of benthic marine infaunal communities in  
2457 British Columbia coastal waters, University of Victoria, Ph.D thesis., 375 pp.
- 2458 Burd, B.J., 1997. Part D: Waste Discharges Discussion Paper. Salmon Aquaculture Review,  
2459 Technical Advisory Team Discussion Papers, B.C. Environmental Assessment Office,  
2460 Victoria, B.C., 3:D1-D118.
- 2461 Burd, B.J., 2000. Ecological Effects and Indicators Analysis for the IONA Receiving  
2462 Environment, in: Greater Vancouver Regional District, (Ed.), Development of a  
2463 Receiving Environment Monitoring Approach to Liquid Waste Management: Progress  
2464 Workshop 2, Burnaby, B.C., 48 pp.
- 2465 Burd, B.J., 2002. Evaluation of mine tailings effects on a benthic marine infaunal community  
2466 over 29 years. *Marine Environmental Research*, 53 481-519.
- 2467 Burd, B.J., 2003a. Review and Prioritization of Benthic Invertebrate Indicator Species, Species  
2468 Assemblages, and Chemical Characteristics that Could be Used in Assessing Effects of  
2469 Marine Finfish Farms on Fish Habitat, Report to the Department of Fisheries and Oceans,  
2470 Pacific Region, 59 pp.

- 2471 Burd, B.J., 2003b. Ecological Significance of IONA 2000-2002 Monitoring Results for Benthic  
2472 Infaunal Communities, in: Greater Vancouver Regional District, 2004. Greater  
2473 Vancouver Regional District. Cautions, Warnings & Triggers: A Process for Protection of  
2474 the Receiving Environment, Appendices: Technical Reports and Monitoring Programs.
- 2475 Burd, B.J., 2003c. Ecological Effects Related to the Outfall Particulates Discharge Determined  
2476 from the Macaulay Point Monitoring Program 1994-2001, Report to Capital Regional  
2477 District, Victoria, British Columbia.
- 2478 Burd, B.J., 2004. Comparative Assessment of Biological and Related Sediment Factors for Outer  
2479 Burrard Inlet: Historical and Current Monitoring Data: Ambient Monitoring Data; Iona  
2480 Monitoring Data, Prepared for the Greater Vancouver Regional District, 83 pp.
- 2481 Burd, B. J., 2006. Analysis of Historic Benthic Biological Data to Determine Validity of the  
2482 Ecological Threshold Concept for Soft Substrate Impacts Related to Coastal BC Fish  
2483 Farm Discharges. Report to BC Ministry of Environment, December 6, 2006, 62 pp.
- 2484 Burd, B.J., Brinkhurst, R.O., 1984. Distribution of the galatheid crab, *Munida quadrispina*  
2485 (Benedict 1902) in relation to oxygen concentrations in British Columbia fjords. Journal  
2486 of Experimental Marine Biology and Ecology 81, 1-20.
- 2487 Burd, B.J., Brinkhurst, R.O., 1987. Macrobenthic infauna from Hecate Strait, B.C. Canadian  
2488 Technical Report of Hydrography and Ocean Sciences 88, 123pp.
- 2489 Burd, B.J., Brinkhurst, R.O., 1990. Vancouver Harbour and Burrard Inlet Benthic Infaunal  
2490 Sampling Program, October 1987. Canadian Technical Report of Hydrography and  
2491 Ocean Sciences 122, 49 pp.
- 2492 Burd, B.J., Brinkhurst, R.O., 1992. Benthic Infaunal Surveys of British Columbia Fjords, 1988 to  
2493 1990. Canadian Data Report of Hydrography and Ocean Sciences 114, 37 pp.

- 2494 Burd, B.J., Glaholt, R., 2000. Survey of benthic infauna at the Manley Creek landfall site at  
2495 Boatswain Bank, British Columbia. Ecostat Research Ltd. and Tera Environmental  
2496 Consultatns (Alta) Ltd. Report to the GSX Pipeline Crossing Project.
- 2497 Burd, B.J., Glaholt, R., Macdonald, V., 2000a. Reconnaissance Level Baseline Survey of  
2498 Benthic Infaunal communities at Ecological Reserve 67 and Adjacent Satellite Channel,  
2499 June 4, 2000. Georgia Strait Crossing Pipeline Ltd., 14 pp. + appendices.
- 2500 Burd, B.J., Macdonald, R.W., Boyd, J., 2000b. Punctuated recovery of sediments and benthic  
2501 infauna: a 19-year study of tailings deposition in a British Columbia fjord. *Marine*  
2502 *Environmental Research* 49, 145-175.
- 2503 Burd, B.J., Macdonald, R.W., Johannessen, S.C., Hill, P.R., van Roodselaar, A., *In Press*. A  
2504 Responses of subtidal benthos of the Strait of Georgia to ambient sediment conditions  
2505 and natural and anthropogenic depositions. *Marine Environmental Research*,
- 2506 Burd, B.J., Moore, D., Brinkhurst, R.O., 1987. Distribution and Abundance of Macrobenthic  
2507 Fauna from Boundary and Mud Bays near the British Columbia/U.S. Border. *Canadian*  
2508 *Technical Report of Hydrography and Ocean Sciences* 84, 1-34.
- 2509 Burgess, R.M., 2000. Characterising and identifying toxicants in marine water: a review of  
2510 marine toxicity identification evaluations (TIEs). *International Journal of Environment*  
2511 *and Pollution* 13, 2-33.
- 2512 Canadian Department of Fisheries and Oceans, 1999a. Manila Clam, DFO Science Stock Status  
2513 Report, C6-03.
- 2514 Canadian Department of Fisheries and Oceans, 1999b. Native Littleneck Clam, DFO Science  
2515 Stock Status Report, C6-02.



- 2516 Canadian Department of Fisheries and Oceans, 2000. Geoduck Clam, DFO Science Stock Status  
2517 Report, C6-05.
- 2518 Canadian Department of Fisheries and Oceans, 2007. Pacific Region, Intergrated Fisheries  
2519 Management Plans, Intertidal Clams, January 1, 2007 to December 31, 2009, Fisheries  
2520 and Oceans Canada, Nanaimo, BC. 71 pp.
- 2521 Capital Regional District, 2000. Core Area Liquid Waste Management Plan, CRD, Victoria,  
2522 British Columbia, 104 pp. + appendices.
- 2523 Capital Regional District, 2003. Macaulay and Clover Point Wastewater and Marine  
2524 Environment Program 2002 Annual Report, Capital Regional District, Environmental  
2525 Services Department, Victoria, B.C., 63 pp. + appendices.
- 2526 Capital Regional District, 2004. Macaulay and Clover Point Wastewater and Marine  
2527 Environment Program 2003 Annual Report, Capital Regional District, Environmental  
2528 Services Department, Victoria, B.C., 93 pp. + appendices.
- 2529 Capital Regional District, 2005. Macaulay and Clover Point Wastewater and Marine  
2530 Environment Program 2004 Annual Report, Capital Regional District, Environmental  
2531 Services Department, Victoria, B.C., 127 pp. + appendices.
- 2532 Carefoot, T., 1977. Pacific Seashores: A guide to intertidal ecology. University of Washington  
2533 Press, Seattle, WA., 208 pp.
- 2534 Carswell, B., Cheesman, S., Anderson, J., 2006. The use of spatial analysis for environmental  
2535 assessment of shellfish aquaculture in Baynes Sound, Vanocuver Island, British  
2536 Columbia, Canada. Aquaculture 253, 408-414.

- 2537 CCME, (Canadian Council of Ministers for the Environment) 1999. Protocol for the Derivation  
2538 of Canadian Sediment Quality Guidelines for the Protection of Aquatic Life, Canadian  
2539 Council of Ministers of the Environment, Ottawa, Ontario. 35 pp. + summary tables.
- 2540 Conlan, K.E., 1977. The effects of wood deposition on from a coastal log handling operation on  
2541 the benthos of a shallow sand bed in Saanich Inlet, British Columbia, University of  
2542 Victoria, M.Sc. thesis, 203 pp.
- 2543 Conlan, K.E., Ellis, D.V., 1979. Effects of wood waste on sand-bed benthos. *Marine Pollution*  
2544 *Bulletin*, 10 262-267.
- 2545 Conway, K.W., 1999. Hexactinellid Sponge Reefs on the British Columbia Shelf: Geological  
2546 and Biological Structure with a Perspective on Their Role in the Shelf Ecosystem.  
2547 Canadian Stock Assessment Secretariat Research Document 99/192, 21 pp.
- 2548 Conway, K.W., Barrie, J.V., Hill, P.R., Austin, W.C., Pickard, K., 2007. Mapping sensitive  
2549 benthic habitats in the Strait of Georgia, coastal British Columbia: Deep-water Sponge  
2550 and Coral Reefs, in: *Current Research*, Geological Survey of Canada, 2007-A2, 6 pp.
- 2551 Conway, K.W., Krautter, M., Barrie, J.V., Neuweiler, M., 2001. Hexactinellid sponge reefs on  
2552 the Canadian continental shelf: A unique "living Fossil". *Geoscience Canada* 28, 71-78.
- 2553 Cook, S., Conway, K.W., Burd, B. *In press*. Status of the glass sponge reefs in the Georgia  
2554 Basin, *Marine Environmental Research*.
- 2555 CORI (Coastal Ocean and Resources Inc), 2002. Lions Gate ROV far-field imaging survey.  
2556 Report prepared for the Greater Vancouver Regional District, Burnaby, B.C., 30 pp. +  
2557 appendices.

- 2558 Coull, B.C., Bell, S.S., 1979. Perspectives in marine meiofauna ecology, in: Livingston, R.J.,  
2559 (Ed.), *Ecological Processes in Coastal Marine Systems*, New York: Plenum Press, pp.  
2560 189-216.
- 2561 Crean, P.B., Murty, T.S. and Stronach, J.A., 1988. *Mathematical modelling of tides and estuarine*  
2562 *circulation: the coastal seas of southern British Columbia and Washington State*.  
2563 Heidelberg: Springer Verlag, 471 pp.
- 2564 Cross, S.F., 1990. *Benthic impacts of salmon farming in British Columbia*, report prepared for  
2565 the Ministry of the Environment, Water Management Branch, Government of British  
2566 Columbia, 78 pp.
- 2567 Cross, S.F., Brinkhurst, R.O., 1991. *Spatial distribution of macrobenthos infauna in Burrard*  
2568 *Inlet: November, 1989*. Canadian Data Report of Hydrography and Ocean Sciences 92,  
2569 40 pp.
- 2570
- 2571 Cross, S.F., Mehlenbacher, N., Lipovsky, S., Williams, A., 2005. *Biological Monitoring of*  
2572 *Salmon Aquaculture Benthic Impacts - Methods Review and Options Analysis*, Report to  
2573 the British Columbia Aquaculture Research and Development Committee, 123 pp. +  
2574 appendices.
- 2575 Davenne, E., Masson, D. 2001. *Water properties in the Straits of Georgia and Juan de Fuca*,  
2576 Fisheries and Oceans Canada, [www-sci.pac.dfo-](http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/straitofgeorgia/JdFG_e.pdf)  
2577 [mpo.gc.ca/osap/projects/straitofgeorgia/JdFG\\_e.pdf](http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/straitofgeorgia/JdFG_e.pdf).
- 2578 Dayton, P.K., 1971. *Competition, disturbance, and community organization: the provision and*  
2579 *subsequent utilization of space in a rocky intertidal community*. *Ecological Monographs*  
2580 41, 351-389.

- 2581 de Brouwer, J.F.C., Wolfstein, K., Ruddy, G.K., Jones, T.E.R., Stal, L.J., 2005. Biogenic  
2582 stabilization of intertidal sediments: The importance of extracellular polymeric  
2583 substances produced by benthic diatoms. *Microbial Ecology* 49, 501-512.
- 2584 De Robertis, A., Eiane, K., Rau, G.H., 2001. Eat and run: anoxic feeding and subsequent aerobic  
2585 recovery by *Orchomene obtusus* in Saanich Inlet, British Columbia, Canada. *Marine*  
2586 *Ecology Progress Series* 219, 221-227.
- 2587 Decho, A.W., 2000. Microbial biofilms in intertidal systems: An overview. *Continental Shelf*  
2588 *Research* 20, 1257-1273.
- 2589 Denny, M.W., Daniel, T.L. and Koehl, M.A.R., 1985. Mechanical limits to size in wave swept  
2590 organisms. *Ecological Monographs* 55, 69-102.
- 2591 Duggins, D.O., 1981. Sea urchins and kelp: The effects of short term changes in urchin diet.  
2592 *Limnology and Oceanography* 26, 391-394.
- 2593 Dumbauld, B.R., Armstrong, D.A., McDonald, T.L., 1993. Use of oyster shell to enhance  
2594 intertidal habitat and mitigate loss of Dungeness crab (*Cancer magister*) caused by  
2595 dredging. *Canadian Journal of Fisheries and Aquatic Sciences* 50, 381-390.
- 2596 Dunn, R., Mullineaux, L. S., Mills, S.W., 1999. Resuspension of postlarval soft-shell clams *Mya*  
2597 *arenaria* through disturbance by the mud snail *Ilyanassa obsolete*. *Marine Ecology*  
2598 *Progress Series* 180, 223-232.
- 2599 Ellis, D.V., 1966. Aerial photography from helicopter as a technique for intertidal surveys.  
2600 *Limnology and Oceanography* 11, 299-301.
- 2601 Ellis, D.V., 1967a. Quantitative Benthic Investigations. I. Satellite Channel biomass summaries  
2602 and major taxon rank orders, February 1965-May 1967. Fisheries Research Board of  
2603 Canada Technical Report 25, 49 pp.

- 2604 Ellis, D.V., 1967b. Quantitative benthic investigations. II. Satellite Channel species data,  
2605 February 1965-May 1967. Fisheries Research Board of Canada Technical Report 35, 170  
2606 pp.
- 2607 Ellis, D.V., 1968a. Quantitative Benthic Investigations. III. Locality and environmental data for  
2608 selected stations (mainly from Satellite Channel, Straits of Georgia and adjacent inlets),  
2609 February 1965-December 1967. Fisheries Research Board of Canada Technical Report  
2610 59, 61 pp. + figures and appendices.
- 2611 Ellis, D.V., 1968b. Quantitative benthic investigations. IV. Biomass summaries and major taxon  
2612 rank orders for selected stations (mainly Straits of Georgia and adjacent inlets), May  
2613 1965-December 1967. Fisheries Research Board of Canada Technical Report 60, 91 pp.
- 2614 Ellis, D.V., 1968c. Quantitative Benthic Investigations. V. Species data from selected stations  
2615 (Straits of Georgia and adjacent inlets), May 1965-May 1966. Fisheries Research Board  
2616 of Canada Technical Report 73, 307 pp.
- 2617 Ellis, D.V., 1970. Ecologically significant species in coastal marine sediments in southern British  
2618 Columbia. *Syensis* 2, 171-182.
- 2619 Ellis, D.V., 1971. A review of marine infaunal community studies in the Strait of Georgia and  
2620 adjacent inlets. *Syensis*, 4, 3-9.
- 2621 Ellis, D.V., 1982. Ocean disposal in British Columbia. *Oceans* 14, 1101-1106.
- 2622 Ellis, D.V., 2002. Underwater biodiversity surveys and biological colonization of the waste  
2623 dump shoreline, (In) Poling, G.W., Ellis, D.V., Murray, J.W., Parsons, T.R. and Pelletier,  
2624 C.A. Underwater Tailing Placement at Island Copper Mine. Society for Mining,  
2625 Metallurgy and Exploration, USA, pp 137-146.

- 2626 Ellis, D.V., 2003. Rocky shore intertidal zonation as a means of monitoring and assessing  
2627 shoreline biodiversity recovery. *Marine Pollution Bulletin*, 46, 305-307.
- 2628 Ellis, D.V., Hoover, P.M., 1990. Benthos on tailings beds from an abandoned coastal mine.  
2629 *Marine Pollution Bulletin* 21, 477-480.
- 2630 Emerson, S., Hedges, J.I., 2003. Sediment diagenesis and benthic flux, in: Elderfield, H., (Ed.),  
2631 *The Oceans and Marine Geochemistry*, Oxford: Elsevier-Pergamon, pp. 293-230.
- 2632 Emmett, B., Bornhold, B.C., Burd, B., 2005. Evaluation of Video and Non-video, Hard Substrate  
2633 Seabed Monitoring Techniques, Prepared for the B.C. Aquaculture Research and  
2634 Development Committee, B.C. Innovation Council, 78 pp.
- 2635 Emmett, B., Thuringer, P., Cook, S. 2006. The development of ROV video survey and data  
2636 classification protocols for monitoring hard seabed substrates, Canadian Science  
2637 Advisory Secretariat Working Paper I2006-04, Fisheries and Oceans Canada.
- 2638 Emmett, B., Thuringer, P., Cook, S., Burd, B., 2007. Evaluation of hard seabed monitoring  
2639 techniques: Development of video survey and data classification protocols: Phase 2,  
2640 report prepared for the Aqua E-Fund, Project AE 03.04-02.02 by Archipelago Marine  
2641 Research, 70 pp. + appendices.
- 2642 Engel, J., Kvitek, R., 1998. Effects of otter trawling on a benthic community in Monterey Bay  
2643 national marine sanctuary. *Conservation Biology* 12, 1204-1214.
- 2644 England, L.A., Thomson, R.E., Foreman, M.G.G., 1996. Estimates of seasonal flushing times for  
2645 the Southern Strait of Georgia. Canadian Technical Report of Hydrography and Ocean  
2646 Sciences 147, 24 pp.
- 2647 Farrow, G.E., Syvitski, J.P.M., Tunnicliffe, V.J., 1983. Suspended particulate loading on the  
2648 macrobenthos in a high turbid fjord: Knight Inlet, British Columbia. *Canadian Journal of*  
2649 *Fisheries and Aquatic Sciences* 40(Supplement 1), 273-288.

- 2650 Fonseca, M.S., Fisher, J.S., 1986. A comparison of canopy friction and sediment movements  
2651 between four species of seagrass with reference to their ecology and restoration. *Marine*  
2652 *Ecology Progress Series* 29, 15-22.
- 2653 Foreman, M.G.G., Sutherland, G., Cummings, P.F., 2004. M2 tidal dissipation around  
2654 Vancouver Island: An inverse approach. *Continental Shelf Research* 24, 2167-2185.
- 2655 Foreman, M.G.G., Walters, R.A., Henry, R.F., Keller, C.P., Dolling, A.G., 1995. A tidal model  
2656 for eastern Juan de Fuca Strait and the southern Strait of Georgia. *Journal of Geophysical*  
2657 *Research* C1-100, 721-740.
- 2658 Freeland, H.J., Farmer, D.M., 1980. Circulation and energetics of a deep, strongly stratified inlet.  
2659 *Canadian Journal of Fisheries and Aquatic Sciences* 37, 1398-1410.
- 2660 Frith, H.R., Searing, G., Wainwright, P., 1994. Methodology for a BC Shoreline biotic mapping  
2661 system, Land Use Coordination Office, Government of British Columbia, Victoria, B.C.
- 2662 G3 Consulting, 2003. Britannia Beach subtidal sampling programs: Final report, prepared for  
2663 Environment Canada, 62 pp.
- 2664 Gargett, A.E., Stucchi, D., Whitney, F., 2003. Physical processes associated with high primary  
2665 production in Saanich Inlet, British Columbia. *Estuarine, Coastal and Shelf Science* 56,  
2666 1141-1156.
- 2667 Gerlach, S.A., Hahn, A.E., Schrage, M., 1985. Size spectra of benthic biomass and metabolism.  
2668 *Marine Ecology Progress Series* 26, 161-173.
- 2669 Gillespie, G.E., Bourne, N.F., 1998. Exploratory intertidal clam surveys in British Columbia-  
2670 1997. *Canadian Manuscript Report of Fisheries and Aquatic Sciences* 2465, 43 pp.
- 2671 Glaholt, R., Burd, B., Haight, R., 2002. Preliminary report on the environmental effects of a  
2672 marine pipeline on nearby soft bottom benthic infaunal communities, Bazan Bay, British

- 2673 Columbia, prepared for Georgia Strait Crossing Pipeline Limited by Tera Environmental  
2674 Services, Ecostat Research Ltd., and Vacilador Productions Ltd., 21 pp. + appendices.
- 2675 Gordon, K., 1997. Sedimentary tracers of sewage inputs to the southern Strait of Georgia.  
2676 University of British Columbia, M.Sc. thesis, 217 pp.
- 2677 Golder Associates Ltd., 2005. Potential environmental effects from the Macaulay and Clover  
2678 Point Outfalls and review of the Wastewater and Marine Environment Program. Report  
2679 prepared for the Capital Regional District, Victoria, BC, Canada. December 2005
- 2680 Goldstein, B.A., Perkins-Visser, E., Wolcott, T.G., Wolcott, D.L., 1996. Nursery role of  
2681 seagrass beds: enhanced growth of juvenile blue crabs (*Callinectes sapidus* Rathbun). J.  
2682 Exp. Mar. Biol. Ecol. 198: 155-173.
- 2683 Griffin, D.A., LeBlonde, P.H., 1990. Estuary/ocean exchange controlled by spring-neap tidal  
2684 mixing. Estuarine Coastal and Shelf Science 30, 275-297.
- 2685 Grout, J.A., Levings, C.D., 2001. Effects of acid mine drainage from an abandoned copper mine,  
2686 Britannica Mines, Howe Sound, British Columbia, Canada on transplanted blue mussels  
2687 (*Mytilus edulis*). Marine Environmental Research 51, 265-288.
- 2688 Gucluer, S.M., Gross, M.G., 1964. Recent marine sediments in Saanich Inlet, a stagnant marine  
2689 basin. Limnology and Oceanography 9, 359-375.
- 2690 GVRD, 2004. Greater Vancouver Regional District cautions, warnings, and triggers: A process  
2691 for protection of the receiving environment, Prepared for the Ministry of Environment  
2692 Land and Air Protection, Greater Vancouver Regional District, Burnaby, B.C., 170 pp. +  
2693 appendices.



- 2694 Hagan, M., McCandless, R., More, B., Colodey, A., 2004. Nearshore contaminated sediment  
2695 investigations at Britannia Beach, British Columbia, Environment Canada Pacific and  
2696 Yukon Region, Regional Program Report, 03-06, 62.
- 2697 Haigh, R., Taylor, F.J.R., 1991. Mosaicism of microplankton communities in the northern Strait  
2698 of Georgia, British Columbia. *Marine Biology* 110, 301-314.
- 2699 Haigh, R., Taylor, F.J.R., Sutherland, T.F., 1992. Phytoplankton ecology of Sechelt Inlet, a fjord  
2700 system on the British Columbia coast. I. General features of the nano- and microplankton.  
2701 *Marine Ecology Progress Series* 89, 117-134.
- 2702 Hannides, A.K., Dunn, S.M., Aller, R.C., 2005. Diffusion of organic and inorganic solutes  
2703 through macrofaunal mucus secretions and tube linings in sediments. *Journal of Marine*  
2704 *Research* 63, 957-981.
- 2705 Harbo, R.M., Marcus, K., Boxwell, T., 1997. Intertidal clam resources (Manila, Littleneck and  
2706 Butter Clam). Volume II: The southern inside waters of Vancouver Island and the British  
2707 Columbia mainland, 16 pp. + maps.
- 2708 Hargrave, B.T. Holmer, M., Newcombe, C.P., 2008. Towards a classification of organic  
2709 enrichment in marine sediments based on biogeochemical indicators. *Marine Pollution*  
2710 *Bulletin*, 56, 810-824.
- 2711 Harper, J.R., 1995. Physical processes overview for the west coast of Vancouver Island, report to  
2712 the Land Use Coordination Office, Victoria, Government of British Columbia.
- 2713 Harper, J.R., Christian, J., Cross, W.E., Frith, R., Searing, G., Thompson, D., 1993a. A  
2714 classification of the marine regions of Canada, Environment Canada, Vancouver, B.C.
- 2715 Harper, J.R., Peters, S., Booth, J., Dickins, D.F., Morris, M. 1993b. Coastal information resource  
2716 inventory, prepared for the Resources Inventory Committee, Province of British

- 2717 Columbia., Victoria, B.C., 81 pp. Available electronically at:  
2718 [http://www.ilmb.gov.bc.ca/risc/o\\_docs/coastal/cir/assets/coastal.pdf](http://www.ilmb.gov.bc.ca/risc/o_docs/coastal/cir/assets/coastal.pdf)
- 2719 Harrison, P.J., 1981. The biological determinants of the structure of harpacticoid copepod  
2720 communities on an estuarine intertidal flat (Fraser River Delta, B.C.), University of  
2721 British Columbia, Ph.D. thesis, 455 pp.
- 2722 Harrison, P.J., Fulton, J.D., Taylor, F.J.R., Parsons, T.R., 1983. Review of the biological  
2723 oceanography of the Strait of Georgia: pelagic environment. *Canadian Journal of*  
2724 *Fisheries and Aquatic Sciences* 40, 1064-1094.
- 2725 Harrison, P.J., Yin, K., 1998. Ecosystem delineation in the Georgia Basin based on nutrients,  
2726 chlorophyll, phytoplankton species and primary production, in: Levings, C.D., Aitkens,  
2727 F., (Eds.), *Approaches to Marine Ecosystem Delineation in the Strait of Georgia:*  
2728 *Proceedings of a D.F.O. workshop, Sidney, B.C., 4-5 November, 1997, Canadian*  
2729 *Technical Report of Fisheries and Aquatic Sciences* 2247, 124-134.
- 2730 Harrison, P.J., Yin, K., Ross, L., Arvai, J., Gordon, K., Bendell-Young, L.I., Thomas, C., 1999.  
2731 The delta foreshore ecosystem: past present status of geochemistry, benthic community  
2732 production and shorebird utilization after sewage diversion, in: Gray, C., Tuominen, T.,  
2733 (Eds.), *Health of the Fraser River Aquatic Ecosystem, Environment Canada, Vancouver,*  
2734 *B.C., pp. 189-210.*
- 2735 Hart, B.S., Hamilton, T.S., Barrie, J.V., 1998. Sedimentation rates and patterns on a deep-water  
2736 delta (Fraser Delta, Canada) integration of high-resolution seismic stratigraphy, core  
2737 lithofacies, and  $^{137}\text{Cs}$  fallout stratigraphy. *Journal of Sedimentary Research* 68, 556-568.

- 2738 Hayashi, K.I., Ogawa, Y., 1987. *Spongicola levigata* sp. nov., a new shrimp associated with a  
2739 hexactinellid sponge from the East China Sea (Decapoda, Stenopodidae). Zoological  
2740 Science (Tokyo) 4, 367-373.
- 2741 Heck, K.J., Able, K., Fahay, M., Roman, C., 1989. Fishes and decapod crustaceans of Cape Cod  
2742 eelgrass meadows: Species composition, seasonal abundance patterns and comparison  
2743 with unvegetated substrates. Estuaries 12, 59-65.
- 2744 Heck, K.L., Hays, G., Orth, R.J., 2003. Critical evaluation of the nursery role hypothesis for  
2745 seagrass meadows. Mar. Ecol. Prog. Ser. 253: 123-136.
- 2746 Hewitt, J.E., Pridmore, D., Thrush, S.F. and Cummings, V.J., 1997. Assessing the Short-Term  
2747 Stability of Spatial Patterns of Macrobenthos in a Dynamic Estuarine System. Limnology  
2748 and Oceanography 42, 282-288.
- 2749 Hickin, E.J., 1989. Contemporary Squamish River sediment flux to Howe Sound. Canadian  
2750 Journal of Earth Sciences, 26, 1953-1963.
- 2751 Hickin, E.J., 1992. An inventory of research conducted in Squamish Basin: Proceedings of the  
2752 Howe Sound environmental workshop (September 30-October 3, 1991, Bowen Island,  
2753 B.C.). Canadian Technical Report of Fisheries and Aquatic Sciences 1879, 43-47.
- 2754 Hill, P.R., Conway K., Lintern, G.D., Meulé, S., Picard, K., Barrie, J.V. *In press*. Sedimentary  
2755 processes and sediment dispersal in the southern Strait of Georgia, BC, Canada. Marine  
2756 Environmental Research.
- 2757 Hodgins, D.O., Hodgins, S.L.M., 2000. A Re-evaluation of Iona effluent solids deposition based  
2758 on sediment grain size characteristics, in: Greater Vancouver Regional District, (Ed.),  
2759 Development of a Receiving Environment Monitoring Approach to Liquid Waste  
2760 Management. Progress Workshop 2 December 6, 2000, Support Material Part 2 of 3 Iona

- 2761 WWTP Receiving Environment, Draft Technical Report, GVRD, Burnaby, B.C., pp. 1.1  
2762 -1.24.
- 2763 Hodgins, D.O., Chapman, P.M., Bailey, H.C., 2000. Lions Gate wastewater treatment plant  
2764 monitoring program, proposed Cycle 1: Environmental monitoring program, Greater  
2765 Vancouver Regional District, Vancouver, BC, Draft Report, 77 pp.
- 2766 Holte, B., Gulliksen, B., 1998. Common macrofaunal dominant species in the sediments of some  
2767 north Norwegian and Svalbard glacial fjords. *Polar Biology* 19, 375-382.
- 2768 Hoos, L.M., Vold, C.L., 1975. The Squamish River Estuary: Status of environmental knowledge  
2769 to 1974, Environment Canada Special Estuary Series Report 2, 361 pp.
- 2770 Hoskins, D.L., Stancyk, S.E., Decho, A.W., 2003. Utilization of algal and bacterial extracellular  
2771 polymeric secretions (EPS) by the deposit-feeding brittlestar *Amphiopholis gracillima*  
2772 (Echinodermata). *Marine Ecology Progress Series* 247, 93-101.
- 2773 Howes, D.E., Harper, J.R., Owens, E., 1994. British Columbia physical shore-zone, British  
2774 Columbia Resource Inventory Committee, Victoria, B.C., 84 pp.
- 2775 Howes, D.E., Wainwright, P., Haggarty, J., Harper, J.R., Owens, E., Reimer, D., Summers, K.,  
2776 Cooper, J., Berg, L., Baird, R., 1993. Coastal resource and oil spill atlas for the southern  
2777 Strait of Georgia, B.C. Ministry of the Environment, Lands and Parks, Environmental  
2778 Emergencies Coordination Office, Victoria, B.C., 317 pp.
- 2779 Howes, D.E., Zacharias, M.A., Harper, J.R., 1996. The Marine ecoregions of British Columbia,  
2780 The Land Use Coordination Office, Government of British Columbia, Victoria, B.C.
- 2781 Huggett, W.S., Thomson, R.E., Woodward, M.J., Douglas, A.N., 1980. Data record of current  
2782 observations, Vol. VII Johnstone Strait, 1976, 1977, 1978, Institute of Ocean Sciences,  
2783 Sidney, B.C., 288 pp.

- 2784 Hunt, H.L., Mullineaux, L.S., 2002. The Roles of Predation and Postlarval Transport in  
2785 Recruitment of the Soft Shell Clam (*Mya arenaria*). *Limnology and Oceanography* 47,  
2786 151-164.
- 2787 Jamieson, G.S., 1988. Vertical distribution and mass mortality of prawns, *Pandalus platyceros*,  
2788 in Saanich Inlet. *Fishery Bulletin* 86, 601-608.
- 2789 Jamieson, G.S., Chew, L., Gillespie, L., Robinson, g., Bendell-Young, L., Heath, W., Bravender,  
2790 B., Tompkins, A., Nishimura, D., Doucett, P., 2001. Phase 0 review of the environmental  
2791 impacts of intertidal shellfish aquaculture in Baynes Sound. Canadian Science Advisory  
2792 Secretariat Research Document 2001/125. URL: [http://www.dfo-](http://www.dfo-mpo.gc.ca/csas/Csas/publications/ResDocs-DocRech/2001/2001_125_e.htm)  
2793 [mpo.gc.ca/csas/Csas/publications/ResDocs-DocRech/2001/2001\\_125\\_e.htm](http://www.dfo-mpo.gc.ca/csas/Csas/publications/ResDocs-DocRech/2001/2001_125_e.htm)
- 2794 Jamieson, G.S., Levings, C.D., Mason, B.C. and Smiley, B.D., 1999. Shorekeepers' guide for  
2795 monitoring Intertidal habitats in Canada's Pacific waters, Fisheries and Oceans Canada,  
2796 Sidney, BC, Modules 1, 2, and 3.
- 2797 Je, J.-G., Belan, T., Levings, C., Koo, B.J., 2003. Changes in benthic communities along a  
2798 presumed pollution gradient in Vancouver Harbour. *Marine Environmental Research* 57,  
2799 121-135.
- 2800 Johannessen, S.C., Macdonald, R.W., Eek, K.M., 2005a. Historical trends in mercury  
2801 sedimentation and mixing in the Strait of Georgia, Canada. *Environmental Science &*  
2802 *Technology* 39, 4361-4368.
- 2803 Johannessen, S.C., Macdonald, R.W., Paton, D.W., 2003. A sediment and organic carbon budget  
2804 for the greater Strait of Georgia. *Estuarine, Coastal and Shelf Science* 56, 845-860.

- 2805 Johannessen, S.C., Macdonald, R.W., Wright, C.A., Burd, B., Shaw, D.P., van Roodselaar, A., *In*  
2806 *Press*. Joined by geochemistry, divided by history: PCBs and PBDEs in the Strait of  
2807 Georgia sediments. *Marine Environmental Research*.
- 2808 Johannessen, S.C., Masson, D., Macdonald, R.W., 2006. Distribution and cycling of suspended  
2809 particles inferred from transmissivity in the Strait of Georgia, Haro Strait and Juan de  
2810 Fuca Strait. *Atmosphere-Oceans* 44, 17-27.
- 2811 Johannessen, S.C., O'Brien, M.C., Denman, K.L., Macdonald, R.W., 2005b. Seasonal and spatial  
2812 variations in the source and transport of sinking particles in the Strait of Georgia, British  
2813 Columbia, Canada. *Marine Geology* 216, 59-77.
- 2814 Kathman, R.D., Cross, S.F., Waldichuk, M., 1984. Effects of wood waste on the recruitment of  
2815 marine benthic communities. *Canadian Technical Report of Fisheries and Aquatic*  
2816 *Sciences* 1284, 50 pp.
- 2817 Kellerhals, P., Murray, J.W., 1969. Tidal flats at Boundary Bay, Fraser River Delta, British  
2818 Columbia. *Bulletin of Canadian Petroleum Geology* 17, 67-91.
- 2819 Kennett, K., McPhee, M.W., 1988. The Fraser River Estuary: An overview of changing  
2820 conditions, Fraser River Estuary Management Program, New Westminster, B.C., 31 pp.
- 2821 Kozloff, E. N., 1987. *Marine invertebrates of the Pacific northwest*. University of Washington  
2822 Press, Seattle, WA., 511 pp.
- 2823 Krautter, M., Conway, K.W., Barrie, J.V., Neuweiler, M., 2001. Discovery of a living dinosaur:  
2824 Globally unique modern hexactinellid sponge reefs off British Columbia, Canada. *Facies*  
2825 44, 265-282.

- 2826 Kristensen, E., 1988. Benthic fauna and biogeochemical processes in marine sediments:  
2827 microbial activities and fluxes, in: Blackburn, T.H., Sorensen, J., (Eds.), Nitrogen  
2828 Cycling in Coastal Marine Environments, John Wiley & Sons, Chichester, pp. 275-299.
- 2829 Kristensen, E., Kostka, J.E., 2005. Macrofaunal burrows and irrigation in marine sediment:  
2830 microbiological and biogeochemical interactions, in: Kristensen, E., Haese, R., Kostka,  
2831 J.E., (Eds.), Interactions between Macro- and Microorganisms in Marine Sediments.  
2832 American Geophysical Union, Washington, D.C., pp. 125-158.
- 2833 Lamb, A., Edgell, P., 1986. Coastal Fishes of the pacific northwest, Madiera Park, B.C., Harbour  
2834 Publishing, 224 pp.
- 2835 Lauzier, R.B., Hand, C.M., Campbell, A., Heizer, S., 1998. A review of the biology and fisheries  
2836 of the horse clams (*Tresus capax* and *Tresus nuttalli*). Canadian Stock Assessment  
2837 Secretariat Research Document 1998/88, 33 pp.
- 2838 LeBlonde, P.H., 1983. The Strait of Georgia: functional anatomy of a coastal sea. Canadian  
2839 Journal of Fisheries and Aquatic Sciences 40, 1033-1063.
- 2840 Levings, C.D., 1980a. Benthic biology of a dissolved oxygen deficiency event in Howe Sound,  
2841 B.C., in: Freeland, H.J., Farmer, D.M., Levings, C.D., (Eds.), Fjord Oceanography, New  
2842 York, Plenum Publishing, pp. 515-522.
- 2843 Levings, C.D., 1980b. Demersal and benthic communities in Howe Sound basin and their  
2844 responses to dissolved oxygen deficiency. Canadian Technical Report of Fisheries and  
2845 Aquatic Sciences,, 951, 27 pp.
- 2846 Levings, C.D., Barry, K.L., Grout, J.A., Piercey, G.E., Marsden, A.D., Coombs, A.P., Mossop,  
2847 B., 2004. Effects of acid mine drainage on the estuarine food web, Britannica Beach,  
2848 Howe Sound, British Columbia, Canada. Hydrobiologia 525, 185-202.

- 2849 Levings, C.D., Coustalin, J.B., 1975. Zonation of intertidal biomass and related benthic data  
2850 from Sturgeon and Roberts Bank, Fraser River Estuary, British Columbia. Fisheries and  
2851 Marine Technical Services 468, 138 pp.
- 2852 Levings, C.D., Foreman, R.E., Tunnicliffe, V.J., 1983. Review of the benthos of the Strait of  
2853 Georgia and contiguous fjords. Canadian Journal of Fisheries and Aquatic Sciences 40,  
2854 1120-1141.
- 2855 Levings, C.D., Jamieson, G.S., 2001. Marine and estuarine riparian habitats and their role in  
2856 coastal ecosystems, Pacific Region. Canadian Science Advisory Secretariat Research  
2857 Document 2001/109, 42 pp.
- 2858 Levings, C.D., McDaniel, N., 1973. Biological observations from the submersible PICES IV  
2859 near Britannia Beach, Howe Sound, BC, Fisheries Research Board Technical Report,  
2860 409, 23 pp.
- 2861 Levings, C.D., McDaniel, N.G., 1974. A unique collection of baseline biological data: Benthic  
2862 invertebrates from an under-water cable across the Strait of Georgia. Fisheries Research  
2863 Board of Canada, Technical Report 441, 19 pp.
- 2864 Levings, C.D., McDaniel, N.G., 1976. Industrial disruption of invertebrate communities on  
2865 beaches in Howe Sound, B.C. Fisheries Marine Services Technical Report 663, 100 pp.
- 2866 Levings, C.D., Samis, S., 2001. Section II site description and oceanography, in: Stehr, C.M.,  
2867 Horiguchi, T., (Eds.), Environmental Assessment of Vancouver Harbour Data Report for  
2868 the PICES Practical Workshop, PICES Scientific Report No. 16, PICES Secretariat,  
2869 Sidney, B.C., pp. 15-21.
- 2870 Levings, C.D., Thom, R.M., 1994. Habitat changes in Georgia Basin: Implications for resource  
2871 management and restoration, in: Wilson, R.C.H., Beamish, R.J., Aikens, F., Bell, J.,



- 2872 (Eds.), Review of the Marine Environment and Biota of Strait of Georgia, Puget Sound  
2873 and Juan de Fuca Strait: Proceedings of the BC/Washington Symposium of the Marine  
2874 Environment, January 13 and 14, 1994. Canadian Technical Report of Fisheries and  
2875 Aquatic Sciences 1948, 330-351.
- 2876 Li, M., Gargett, A., Denman, K., 1999. Seasonal and interannual variability of estuarine  
2877 circulation in a box model of the Strait of Georgia and Juan de Fuca Strait. *Atmosphere-*  
2878 *Ocean* 37, 1-19.
- 2879 Llansó, R.J., Aasen, S., Welch, K., 1998. Marine sediment monitoring program: II. Distribution  
2880 and structure of benthic communities in Puget Sound 1989-1993, Washington State  
2881 Department of Ecology: Environmental investigations and laboratory services program,  
2882 Olympia, Washington, 114 pp. + appendices.
- 2883 Long, E.R., Hong, C.B., Severn, C.G., 2001. Relationships between acute sediment toxicity in  
2884 laboratory tests and abundance and diversity of benthic infauna in marine sediments: a  
2885 review. *Environmental Toxicology and Chemistry* 20, 46-60.
- 2886 Macdonald, R.W., Crecelius, E.A., 1994. Marine sediments in the Strait of Georgia, Juan de  
2887 Fuca Strait and Puget Sound: What can they tell us about contamination? in: Wilson,  
2888 R.C.H., Beamish, R.J., Aitkens, F., Bell, J., (Eds.), Review of the Marine Environment  
2889 and Biota of Strait of Georgia, Puget Sound and Juan de Fuca Strait. Canadian Technical  
2890 Report of Fisheries and Aquatic Sciences 1948, 101-137.
- 2891 Macdonald, R.W., Cretney, W.J., Crewe, N., Paton, D., 1992. A history of octachlorodibenzo-p-  
2892 dioxin, 2,3,7,8-tetrachlorodibenzofuran and 3,3', 4-4'-tetrachlorobiphenyl contamination  
2893 in Howe Sound, British Columbia. *Environmental Science & Technology* 26, 1544-1550.

- 2894 Macdonald, R.W., Johannessen, S.C., Gobeil, C., Wright, C.A., Burd, B.J., van Roodselaar, A.,  
2895 *In press*. Sediment redox tracers in the Strait of Georgia sediments - can they inform us  
2896 of the loadings of organic carbon from municipal wastewater? *Marine Environmental*  
2897 *Research*.
- 2898 Macdonald, R.W., Macdonald, D.M., O'Brien, M.C., Gobeil, C., 1991. Accumulation of heavy  
2899 metals (Pb, Zn, Cu, Cd), carbon and nitrogen in sediments from the Strait of Georgia,  
2900 B.C., Canada. *Marine Chemistry* 34, 109-135.
- 2901 Mackas, D.L., Louttit, G.C., 1988. Aggregation of the copepod *Neocalanus plumchrus* at the  
2902 margin of the Fraser River plume in the Strait of Georgia. *Bulletin of Marine Science* 43,  
2903 810-824.
- 2904 Madrone Consulting Ltd., 1993. Bamberton: Biological inventory and evaluation, 1992-1993,  
2905 prepared for South Island Development Corporation, Victoria, B.C.
- 2906 Marinone, S.G., Pond, S., 1996. A three-dimensional model of deep water renewal and its  
2907 influence on residual currents in the central Strait of Georgia, Canada. *Estuarine, Coastal*  
2908 *and Shelf Science* 43, 183-204.
- 2909 Masson, D., 2002. Deep water renewal in the Strait of Georgia. *Estuarine, Coastal and Shelf*  
2910 *Science* 54, 115-126.
- 2911 Masson, D., Cummings, P.F., 2000. Fortnightly modulation of estuarine circulation in Juan de  
2912 Fuca Strait. *Journal of Marine Research* 58, 439-463.
- 2913 Masson, D., Cummings, P.F., 2004. Observations and modeling of seasonal variability in the  
2914 Straits of Georgia and Juan de Fuca. *Journal of Marine Research* 62, 491-516.
- 2915 Maurer, D., Aprill, G., 2007. Intertidal benthic invertebrates and sediment stability at the mouth  
2916 of Delaware Bay. *International Review of Hydrobiology* 64, 379-403.

- 2917 McDaniel, N.G., 1973. A Survey of Benthic Macroinvertebrate Fauna and Solid Pollutants in  
2918 Howe Sound. Fisheries Research Board of Canada Technical Report 385, 64 pp.
- 2919 McGreer, E.R., Moore, D.M., Sibert, J.R., 1984. Study of the recovery of intertidal benthos after  
2920 removal of log booms, Nanaimo River Estuary, British Columbia. Canadian Technical  
2921 Report of Fisheries and Aquatic Sciences 1246, vii + 63 pp.
- 2922 McLaren, P., 1994. Sediment transport in Vancouver Harbour: Implications to the fate of  
2923 contaminated sediments and/or dredged material disposal, A Report for the Burrard Inlet  
2924 Environmental Action Program, Vancouver, B.C., 25 pp. + appendices.
- 2925 McLaren, P., Crentey, W.J., Powys, R.I., 1993. Sediment pathways in a British Columbia fjord  
2926 and their relationship with particle associated contaminants. Journal of Coastal Research  
2927 9, 1026-1043.
- 2928 McLaren, P., Ren, P., 1995. Sediment transport and its environmental implications in the lower  
2929 Fraser River and Fraser Delta, A Report for Environment Canada, DOE FRAP 1993.03,  
2930 Vancouver, B.C., 38 pp.
- 2931 McPherson, C.A., Bailey, H.C., Chapman, M.K., Lee, M.K., Burd, B.J., Fanning, M.L., Paine,  
2932 M.D., Hamilton, M.C., Chen, F., 2003. Iona Deep-sea Outfall, 2002 Environmental  
2933 monitoring program: Sediment effects survey, prepared for the Greater Vancouver  
2934 Regional District by EVS Consultants Ltd., Burnaby, B.C., 223 pp. + appendices.
- 2935 McPherson, C.A., Chapman, M.K., Fanning, M.L., Olson, J., Chen, F., 2004a. Georgia Strait  
2936 ambient monitoring program - Data report, prepared for the Greater Vancouver Regional  
2937 District by EVS Consultants Ltd, Burnaby, B.C., 28 pp. + appendices.
- 2938 McPherson, C.A., Chapman, M.K., Lee, M.K., Burd, B.J., Fanning, M.L., Hamilton, M.C.,  
2939 Chen, F., 2004b. Iona Deep-sea Outfall, 2003 Environmental monitoring program:

- 2940 Sediment effects survey, prepared for the Greater Vancouver Regional District by EVS  
2941 Consultants Ltd., Burnaby, BC, 262 pp. + appendices.
- 2942 McPherson, C.A., Chapman, M.K., Lee, M.K., Fanning, M.L., Olson, J., Chen, F., 2004c. Lions  
2943 Gate Outfall, 2003 Environmental monitoring program: Sediment effects survey,  
2944 prepared for the Greater Vancouver Regional District by EVS Consultants Ltd., Burnaby,  
2945 B.C., 99 pp. + appendices.
- 2946 McPherson, C.A., Chapman, M.K., McKinnon, S., Burd, B.J., Fanning, M.L., Olson, J.,  
2947 Hamilton, M.C., Chen, F., 2005a. Iona Deep-sea Outfall, 2004 Environmental monitoring  
2948 program: Sediment effects survey, prepared for the Greater Vancouver Regional District  
2949 by EVS Consultants Ltd., Burnaby, B.C., 222 pp. + appendices.
- 2950 McPherson, C.A., Chapman, M.K., McKinnon, S., Burd, B.J., Fanning, M.L., Olson, J.,  
2951 Hamilton, M.C., Chen, F., 2006a. Iona Deep-sea Outfall, 2005 Environmental monitoring  
2952 program: Sediment effects survey, prepared for the Greater Vancouver Regional District  
2953 by EVS Consultants Ltd., Burnaby, B.C., 262 pp. + appendices.
- 2954 McPherson, C.A., Chapman, M.K., McKinnon, S., Burd, B.J., Fanning, M.L., Olson, J.,  
2955 Hamilton, M.C., Chen, F., 2007a. Iona Deep-sea Outfall, 2006 Environmental monitoring  
2956 program: Sediment effects survey, prepared for the Greater Vancouver Regional District  
2957 by EVS Consultants Ltd., Burnaby, B.C., 240 pp. + appendices.
- 2958 McPherson, C.A., Chapman, P.M., McKinnon, S.J., Burd, B.J., Fanning, M.L., Olson, J.,  
2959 Markovic-Mirovic, N, 2006b. Lions Gate Outfall, 2005 Sediment Effects Survey. Final  
2960 Report prepared for the Greater Vancouver Regional District (GVRD), Burnaby, BC by  
2961 Golder Associates Ltd. North Vancouver, BC. 222 pp. + appendices.

- 2962 McPherson, C.A., Chapman, P.M., McKinnon, S.J., Burd, B.J., Fanning, M.L., Olson, J., Ross-  
2963 Easton, H., Brooks, G., 2007b. Lions Gate Outfall, 2006 Sediment Effects Survey. Prepared  
2964 for the Greater Vancouver Regional District (GVRD), Burnaby, BC by Golder Associates  
2965 Ltd. North Vancouver, BC. 238 pp. + appendices.
- 2966  
2967 McPherson, C.A., Chapman, M.K., McKinnon, S.J., Fanning, M.L., Burd, B.J., Olson, J., Chen,  
2968 F., Brooks, G., 2005b. Lions Gate Outfall, 2004 Sediment Effects Survey, Prepared for  
2969 the Greater Vancouver Regional District by EVS Consultants Ltd, Burnaby, BC, 212  
2970 pp.+ appendices.
- 2971 Møller, M.M., Nielsen, L.P., Jørgensen, B.B., 1985. Oxygen responses and mat formation by  
2972 *Beggiatoa* spp. Applied and Environmental Microbiology 50, 373-382.
- 2973 Mosher, D.C., Currie, R.G., Sullivan, D., 1997. Monitoring of ocean disposal using side-scan  
2974 mosaicing. Leading Edge 16, 1667-1669.
- 2975 MWLAP, 2002. Protocols for Marine environmental monitoring in support of finfish aquaculture  
2976 waste control regulations, Ministry of Water Land and Parks, Environmental Protection  
2977 Division, Victoria, B.C., 29 pp.
- 2978 NEMP, 2002. Final report of the log storage working group, prepared for the Nanaimo Estuary  
2979 Management Plan Steering Committee, Ministry of Integrated Land and Management  
2980 Bureau, Government of British Columbia, 27 pp.
- 2981 Newell, R. C., Seiderer, L. J., Hitchcock, D. R., 1998. The impact of dredging works in coastal  
2982 waters: a review of the sensitivity to disturbance and subsequent recovery of biological  
2983 resources on the sea bed. Oceanography and Marine Biology: An Annual Review 36,  
2984 127-178.

- 2985 Nickel, L.A., Atkinson, R.J.A., 1995. Functional morphology of burrows and trophic modes of  
2986 three thalassinidean shrimp species and a new approach to classification of thalassinidean  
2987 burrow morphology. *Marine Ecology Progress Series* 128, 181-197.
- 2988 Orvain, F., Le Hir, P., Sauriau, P.-G., 2003. A model of fluff layer erosion and subsequent bed  
2989 erosion in the presence of the bioturbator, *Hydrobia ulvae*. *Journal of Marine Research*  
2990 61, 823-851.
- 2991 Otte, G., Levings, C.D., 1975. Distribution of macroinvertebrates communities on mudflat  
2992 influenced by sewage. Fraser River Estuary, British Columbia. Fisheries Marine Series  
2993 Technical Report 476, 78 pp.
- 2994 Paine, Ledge and Associates, 2004. Analyses of Macaulay Point sediment quality data: 1990-  
2995 2003. Prepared for Capital Region District, Environmental Services, 137 pp. Paine,  
2996 Ledge and Associates (PLA). North Vancouver, British Columbia.
- 2997 Paine, M.D., 2003. Environmental significance of sediment quality and tissue residue monitoring  
2998 data for the GVRD Iona and Lions Gate outfall study areas. Draft Report, Prepared for  
2999 the Greater Vancouver Regional District (GVRD) by Paine, Ledge and Associates (PLA),  
3000 North Vancouver, 31 pp. + Tables + Figures.
- 3001 Paine, R.T., Vadas, R.L., 1969. The effects of grazing by sea urchins. *Strongylocentrotus* spp., on  
3002 benthic algal populations. *Limnology and Oceanography* 14, 710-719.
- 3003 Palsson, W.A., Hoffmann, S., Clarke, P., Beam, J., 2003. Results from the 2001 transboundary  
3004 trawl survey of the southern Strait of Georgia, San Juan Archipelago and adjacent waters,  
3005 Report for the Washington Department of Fish and Wildlife, 117 pp.

- 3006 Parsons, T.R., Stronach, J., Borstad, G.A., Louttit, G., Perry, R.I., 1981. Biological fronts in the  
3007 Strait of Georgia, British Columbia, and their relation to recent measurements of primary  
3008 productivity. *Marine Ecology Progress Series* 6, 237-242.
- 3009 Pawlowicz, R., 2001. A tracer method for determining transport in two-layer systems, applied to  
3010 the Strait of Georgia/Haro Strait/Juan de Fuca Strait estuarine system. *Estuarine, Coastal  
3011 and Shelf Science* 52, 491-503.
- 3012 Pawlowicz, R., 2002. Observations and linear analysis of estuarine flow and sill-generated  
3013 internal tides in Haro Strait. *Journal of Geophysical Research* 107, [np], DOI:  
3014 10.1029/2000JC000504.
- 3015 Pearson, T.H., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment  
3016 and pollution of the marine environment. *Oceanography and Marine Biology Annual  
3017 Review* 16, 229-311.
- 3018 PICES (Ed.), 2001. Environmental assessment of Vancouver Harbour data report for the PICES  
3019 practical workshop, North Pacific Marine Sciences Organization (PICES) Secretariat,  
3020 PICES, Sidney, B.C., 203 pp.
- 3021 Pickard, G.L., Giovando, L.F., 1960. Some observations of turbidity in British Columbia inlets.  
3022 *Limnology and Oceanography* 5, 162-170.
- 3023 Pohle, G., Frost, B., Findlay, R., 2001. Assessment of regional benthic impact of salmon  
3024 mariculture within the Letang Inlet, Bay of Fundy. *ICES Journal of Marine Science* 58,  
3025 417-426.
- 3026 Post, A.L., Wassenberg, T.J., Passlow, V., 2006. Physical surrogates for macrofaunal  
3027 distributions and abundance in a tropical gulf. *Marine and Freshwater Research* 57, 469-  
3028 483.

- 3029 Prior, D.B., Bornhold, B.D., Wiseman, W.J.J., Lowe, D.R., 1987. Turbidity current activity in a  
3030 British Columbia fjord. *Science* 237, 1330-1333.
- 3031 Probert, P.K., 1984. Disturbance, sediment stability, and trophic structure of soft-bottom  
3032 communities. *Journal of Marine Research* 42, 893-921.
- 3033 Ragnarsson, S.A., Raffaelli, D., 1999. Effects of the mussel *Mytilus edulis* L. on the  
3034 invertebrate fauna of sediments. *J. Exp. Mar. Biol. Ecol.* 241, 31-43.
- 3035 Reid, B.J., Baumann, J., 1985. Preliminary laboratory study of the effects of burial by  
3036 AMAX/Kitsault mine tailings on marine invertebrates. Canadian Manuscript Report of  
3037 Fisheries and Aquatic Sciences 1781, 45 pp.
- 3038 Rescan Environmental Services Ltd., 1988. Preliminary environmental overview of proposed  
3039 ferrochromium production facility Bamberton, B.C., prepared for the Ministry of  
3040 Regional Development, Government of British Columbia.
- 3041 Rhoads, D.C., Young, D.K., 1970. Influence of deposit-feeding organisms on sediment stability  
3042 and community trophic structure. *Journal of Marine Research* 28, 150-178.
- 3043 Roegner, C., Andre, C., Lindegarth, M., Eckman, J.E., Grant, J., 1995. Transport of recently  
3044 settled soft-shell clams (*Mya arenaria* L.) in laboratory flume flow. *Journal of*  
3045 *Experimental Marine Biology and Ecology* 187, 13-26.
- 3046 Rowe, G., Sibuet, M., Deming, J., Khripoundoff, A., Tietjen, J., Macko, S., Theroux, R., 1991.  
3047 'Total' sediment biomass and preliminary estimates of organic carbon residence time in  
3048 deep-sea benthos. *Marine Ecology Progress Series* 79, 99-114.
- 3049 Samis, S.C., Liu, S.D., Wernick, B.G., Nassichuk, M.D., 1999. Mitigation of fisheries impacts  
3050 from the use and disposal of wood residue in British Columbia and the Yukon. Canadian  
3051 Technical Report of Fisheries and Aquatic Sciences 2296, viii + 91 pp.



- 3052 Schwinghamer, P., 1981. Characteristic size distributions of integral benthic communities.  
3053 Canadian Journal of Fisheries and Aquatic Sciences 38, 1255-1263.
- 3054 Schwinghamer, P., 1983. Generating ecological hypotheses from biomass spectra using causal  
3055 analysis: A benthic example. Marine Ecology Progress Series 13, 151-166.
- 3056 Seacology, Pacific Marine Life Surveys Inc., Tera Environmental Consultants (Alta.) Ltd., 2001.  
3057 Biological survey and assessment of benthic habitats for a proposed Manley Creek  
3058 pipeline landfall at Boatswain Bank, British Columbia-July 2000, prepared for Georgia  
3059 Strait Crossing Pipeline Ltd., 47 pp. + appendices.
- 3060 Seed, R., Suchanek, T.H., 1972. Population and community ecology of *Mytilus*, in: Gosling,  
3061 E.M., (Ed.), The Mussel *Mytilus*: Ecology, Physiology, Genetics, Culture, Amsterdam,  
3062 Elsevier Scientific, pp. 87-169.
- 3063 Shang, D.Y., Macdonald, R.W., Ikonomu, M.G., 1999. Persistence of nonylphenol and  
3064 ethoxylate surfactants and their principle primary degradation products in sediments  
3065 from near a municipal outfall in the Strait of Georgia, British Columbia, Canada.  
3066 Environmental Science & Technology 33, 1366-1372.
- 3067 Sibert, J.R., 1979. Detritus and juvenile salmon production in the Nanaimo Estuary: 2.  
3068 Meiofauna available as food to juvenile chum salmon (*Oncorhynchus keta*). Journal of  
3069 the Fisheries Research Board of Canada 36, 497-503.
- 3070 Sibert, J.R., 1981. Intertidal hyperbenthic populations in the Nanaimo Estuary. Marine Biology  
3071 64, 259-265.
- 3072 Sibert, J.R., Brown, T.J., Harpham, V.J., Kask, B.J., 1979. Meiofauna counts in relation to  
3073 intertidal log storage on the Nanaimo River delta: Spring 1978. Fisheries and Marine  
3074 Service Data Report 149, 105 pp.

- 3075 Sibert, J.R., Harpham, V.J., 1979. Effects of intertidal log storage on the meiofauna and  
3076 interstitial environment of the Nanaimo River delta. Technical Report of the Fisheries  
3077 Marine Service (Canada) 833, 31 pp.
- 3078 Smith, A.L., 1981. Comparison of macrofaunal invertebrates in sand dollar (*Dendraster*  
3079 *excentricus*) beds and in adjacent areas free of sand dollars. *Marine Biology* 65, 191-198.
- 3080 Smith, J.R., Fong, P., Ambrose, R. F., 2006. Dramatic declines in mussel bed community  
3081 diversity : Response to climate change? *Ecology* 87, 1153-1161.
- 3082 Snyder, S.W., Hale, W.R., Kontrovitz, M., 1990. Assessment of Postmortem Transportation of  
3083 Modern Benthic Foraminifera of the Washington Continental Shelf. *Micropaleontology*,  
3084 36, 259-282.
- 3085 Spaulding, H., Foster, M.S., Heine, J.N., 2003. Composition, distribution, and abundance of  
3086 deep-water (>30 m) macroalgae in central California. *Journal of Phycology* 39, 273-284.
- 3087 Stacey, M.W., Pond, S., 2003. The dependence of the currents and the density on the spring-neap  
3088 cycle and the diurnal-inequality in Burrard Inlet, British Columbia: simulations and  
3089 observations. *Journal of Physical Oceanography* 33, 2366-2374.
- 3090 Stacey, M.W., Pond, S., LeBlonde, P.H., 1991. Flow dynamics in the Strait of Georgia, British  
3091 Columbia. *Atmosphere-Ocean* 29, 1-13.
- 3092 Stehr, C.M., Horiguchi, T., (Eds.), 2001. Environmental assessment of Vancouver Harbour, data  
3093 report for the PICES practical workshop 16, North Pacific Marine Sciences Organization  
3094 (PICES) Secretariat, 205 pp.
- 3095 Stephenson, T.A., Stephenson, A., 1961a. Life between tidemarks in North America. IVA.  
3096 Vancouver Island II. *Journal of Ecology*, 49, 1-29.

- 3097 Stephenson, T.A., Stephenson, A., 1961a. Life between tidemarks in North America. IVB.  
3098 Vancouver Island II. *Journal of Ecology*, 49, 227-243.
- 3099 Stephenson, T.A., Stephenson, A., 1972. Life between tidemarks on rocky shores. Freeman,  
3100 USA, 425 pp.
- 3101 Stockner, J.G., Cliff, D.D., Shortreed, K.R.S., 1979. Phytoplankton ecology of the Strait of  
3102 Georgia, British Columbia. *Journal of the Fisheries Research Board of Canada* 36, 657-  
3103 666.
- 3104 Striplin, P., 1996. Development of reference value ranges for benthic infauna assessment  
3105 endpoints in Puget Sound, Washington, State Department of Ecology Sediment  
3106 Management Unit, 44 pp. + appendices.
- 3107 Stubblefield, W.A., Servos, M., Gersberg, R.M., Riley, C., Simpson, D., Smith, D., Wells, P.,  
3108 2006. Scientific and technical review. Capital Regional District core area Liquid Waste  
3109 Management Plan, Submitted to the Capital Regional District, Victoria B.C. by the  
3110 Scientific and Technical Review Panel, 131 pp.
- 3111 Stucchi, D.J., Sutherland, T., Levings, C., Higgs, D., 2005. Near-field depositional model for  
3112 salmon aquaculture waste, in: Hargrave, B.T., (Ed.), *Handbook of Environmental*  
3113 *Chemistry: The Environmental Effects of Marine Finfish Aquaculture*, Volume 5, Part M,  
3114 Springer-Verlag, Berlin, pp. 157-179.
- 3115 Suchanek, T.H., 1979. The *Mytilus californianus* community: studies on the composition,  
3116 structure, organization and dynamics of a mussel bed, University of Washington, Ph.D.  
3117 thesis, 286 pp.
- 3118 Swinbanks, D.D., Murray, J.W., 1981. Biosedimentological zonation of Boundary Bay tidal  
3119 flats, Fraser River Delta, British Columbia. *Sedimentology* 28, 201-237.

- 3120 Taylor, F.J.R., Haigh, R., Sutherland, T.H., 1994. Phytoplankton ecology of Sechelt Inlet, a fjord  
3121 system on British Columbia coast. II. Potentially harmful species. *Marine Ecology*  
3122 *Progress Series* 103, 151-164.
- 3123 Thompson, D., Cooke, W., 1991. Enhancement of hardshell clam habitat by beach gravelling, in:  
3124 Puget Sound Water Quality Action Team (Eds.), *Puget Sound Research '91*. Seattle,  
3125 Washington, Proceedings, pp 521-527.
- 3126 Thomson, R.E., 1976. Tidal currents and estuarine-type circulation in Johnstone Strait, British  
3127 Columbia. *Journal of the Fisheries Research Board of Canada* 33, 2242-2264.
- 3128 Thomson, R.E., 1977. Currents in Johnstone Strait, British Columbia: supplementary data on the  
3129 Vancouver Island side. *Journal of the Fisheries Research Board of Canada*, 34 697-703.
- 3130 Thomson, R.E., 1981. Oceanography of the British Columbia Coast. *Canadian Special*  
3131 *Publication of Fisheries and Aquatic Sciences* 56, 235-258.
- 3132 Thomson, R.E., 1994. Physical oceanography of the Strait of Georgia-Puget Sound-Juan de Fuca  
3133 Strait system, in: Wilson, R.C.H., Beamish, R.J., Aitkens, F., Bell, J., (Eds.), *Review of*  
3134 *the Marine Environment and Biota of Strait of Georgia, Puget Sound and Juan de Fuca*  
3135 *Strait*. *Canadian Technical Report of Fisheries and Aquatic Sciences* 1948, 36-100.
- 3136 Thomson, R.E., 1998. Ecosystem classification of the Strait of Georgia: Physical oceanographic  
3137 delineation, in: Levings, C.D., Pringle, J.D., Aikens, F., (Eds.), *Approaches to Marine*  
3138 *Ecosystem Delineation in the Strait of Georgia*. Proceedings from a DFO Workshop,  
3139 Sidney, B.C. November, 1997. *Canadian Technical Report of Fisheries and Aquatic*  
3140 *Sciences* 2247, 112-123.

- 3141 Thomson, R.E., Foreman, M.G.G., 1998. Basin areas and volumes of coastal southwest British  
3142 Columbia and northwest Washington. Canadian Technical Report of Fisheries and  
3143 Aquatic Sciences 196, 17 pp.
- 3144 Thomson, R.E., Huggett, W.S., 1980. M2 baroclinic tides in Johnstone Strait, British Columbia.  
3145 Journal of Physical Oceanography 10, 1509-1539.
- 3146 Thomson, R.E., Huggett, W.S., Kuwahara, L.S.C., 1980a. Data record of current observations  
3147 Vol. VIII Discovery Passage, Johnstone Strait and Queen Charlotte Strait, Part 1 - water  
3148 property observations, 1976, 1977, 1978, 1979. Institute of Ocean Sciences, Sidney, B.C.,  
3149 262 pp.
- 3150 Thomson, R.E., Huggett, W.S., Kuwahara, L.S.C., 1980b. Data record of current observations  
3151 Vol. VIII, Discovery Passage, Johnstone Strait and Queen Charlotte Strait, Part 2-  
3152 appendices A to E, Institute of Ocean Sciences, Sidney, B.C., 809 pp.
- 3153 Thomson, R.E., Mihaly, S.F., Kulikov, E.A., 2007. Estuarine versus transient flow regimes in  
3154 Juan de Fuca Strait. Journal of Geophysical Research-Oceans 112, doi:  
3155 10.1029/2006JC003925.
- 3156 Tito de Morais, L., Bodiou, J.Y., 1984. Predation on meiofauna by juvenile fish in a western  
3157 Mediterranean flatfish nursery ground. Marine Biology 82, 209-215.
- 3158 Tunnicliffe, V., 1981. High species diversity and abundance of the epibenthic community in an  
3159 oxygen-deficient basin. Nature 294, 354-356.
- 3160 Tunnicliffe, V., 2000. A fine-scale record of 130 years of organic carbon deposition in an anoxic  
3161 fjord, Saanich Inlet, British Columbia. Limnology and Oceanography 45, 1380-1387.
- 3162 Tunnicliffe, V., Syvitski, J.P.M., 1983. Corals move boulders: An unusual mechanism of  
3163 sediment transport. Limnology and Oceanography 28, 564-568.

- 3164 Tunnicliffe, V., Wilson, K., 1988. Brachipod populations: distribution in fjords of British  
3165 Columbia (Canada) and tolerance of low oxygen concentrations. *Marine Ecology*  
3166 *Progress Series* 47, 117-128.
- 3167 Wainwright, P., Harper, J.R., Searing, G.F., Howes, D., 1995. Ecological classification within  
3168 British Columbia's marine regions: Methodology report, British Columbia Land Use  
3169 Coordination Office, Victoria, BC, 17 pp.
- 3170 Waldichuk, M., 1957. Physical oceanography of the Strait of Georgia, British Columbia. *Journal*  
3171 *of the Fisheries Research Board of Canada* 14, 321-486.
- 3172 Walker, D., 1995. Shellfish Contamination, in: Calder, A.M., Mann, G.S., (Eds.), Saanich Inlet  
3173 study: Synthesis workshop summary, April 25/26, prepared for the Water Quality  
3174 Branch, British Columbia Ministry of Environment, Lands and Parks by EVS  
3175 Environmental Consultants Ltd., and Sea Science, Vancouver, B.C., pp. 61-90.
- 3176 Wang, F., Chapman, P.M., 1999. Biological implications of sulfide in sediment-a review  
3177 focusing on sediment toxicology. *Environmental Toxicology and Chemistry* 18, 2526-  
3178 2532.
- 3179 Warwick, R.M., Clarke, K.R., 1993. Comparing the severity of disturbance: A meta-analysis of  
3180 marine macrobenthic community data. *Marine Ecology Progress Series* 92, 221-231.
- 3181 Warwick, R.M., Dshfield, S.L., Somerfield, P.J., 2006. The integral structure of a benthic  
3182 infaunal assemblage. *Journal of Experimental Marine Biology and Ecology* 330, 12-18.
- 3183 Watling, L., Norse, E.A., 1998. Disturbance of the seabed by mobile fishing gear: A comparison  
3184 to forest clearcutting. *Conservation Biology* 12, 1180-1197.
- 3185 Watson, J., 1998. A review of ecosystem classification: Delineating the Strait of Georgia, in:  
3186 Levings, C.D., Pringle, J.D., Aikens, F. (Eds.), *Approaches to Marine Ecosystem*

- 3187 Delineation in the Strait of Georgia, Proceedings from a DFO Workshop, Sidney, B.C.  
3188 November, 1997. Canadian Technical Report of Fisheries and Aquatic Sciences 2247, 3-  
3189 71.
- 3190 West, P., Fyles, T.M., King, B., Peeler, D.C., 1994. The effects of human activity on the marine  
3191 environment of the Georgia basin: Present waste loadings and future trends, in: Wilson,  
3192 R.C.H., Beamish, R.J., Aitkens, F., Bell, J. (Eds.), Review of the Marine Environment  
3193 and Biota of Strait of Georgia, Puget Sound and Juan de Fuca Strait. Canadian Technical  
3194 Report of Fisheries and Aquatic Sciences 1948, 9-35.
- 3195 Whiteley, J., Bendell-Young, L.I., 2007. Ecological implications of intertidal mariculture:  
3196 observed differences in bivalve community structure between farm and reference sites.  
3197 Journal of Applied Ecology 44, 495-505.
- 3198 Williams, G.L. & Associates Ltd., 1991. Coastal habitat inventory, in: The town of Bamberton  
3199 Review Process. VII. II. Technical Background South Island, Prepared for the Ministry of  
3200 Environment, Lands and Parks, Water Quality Branch, Government of British Columbia,  
3201 pp. 113-120.
- 3202 Wilson, R.C.H., Beamish, R.J., Aikens, F., Bell, J., 1994. Review of the marine environment and  
3203 biota of the Strait of Georgia, Puget Sound and Juan de Fuca Strait. Proceedings of the  
3204 BC/Washington Symposium on the Marine Environment, January 13 & 14, 1994.  
3205 Canadian Technical Report of Fisheries and Aquatic Sciences 1948, 390 pp.
- 3206 Wilson, R.C.H., McKinnon, S.J., 2003. The Point Grey ocean disposal site, 1975-200: A 25-Year  
3207 Review, Prepared for the Disposal At Sea Program, Environment Canada, Victoria, B.C.,  
3208 118 pp.

- 3209 Wlodarska-Kowalczyk, M., Pearson, T.H., Kendall, M.A., 2005. Benthic response to chronic  
3210 natural physical disturbance by glacial sedimentation in an Arctic fjord. *Marine Ecology*  
3211 *Progress Series* 303, 31-41.
- 3212 Wright, C.A., Johannessen, S.C., Macdonald, R.W., Burd, B.J., Hill, P.R., van Roodselaar, A.,  
3213 Bertold, S., In press. The Strait of Georgia ambient monitoring program, phase I 2002-  
3214 2007: Sediment and benthos. *Canadian Data Report of Fisheries and Aquatic Sciences*,  
3215 XX, xx.
- 3216 Wright, C.A., Pringle, J.D., 2001. Race Rocks pilot marine protected area: An ecological  
3217 Overview. *Canadian Technical Report of Fisheries and Aquatic Sciences* 2353, 93 pp.
- 3218 Wright, C., Taekema, B., Burd, B., McGreer, E., 2007a. Salmon aquaculture environmental  
3219 monitoring data report. Results of sampling program for year 2000, prepared for the  
3220 Ministry of the Environment, province of British Columbia, Nanaimo, B.C. abstract only  
3221 URL: [http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon\\_farming.htm](http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon_farming.htm).
- 3222 Wright, C., Taekema, B., Burd, B., McGreer, E., 2007b. Salmon aquaculture environmental  
3223 monitoring data report. Results of sampling program for year 2001, prepared for the  
3224 Ministry of the Environment, province of British Columbia, Nanaimo, B.C. abstract only  
3225 URL: [http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon\\_farming.htm](http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon_farming.htm).
- 3226 Wright, C., Taekema, B., Burd, B., McGreer, E.R., 2007c. Salmon aquaculture environmental  
3227 monitoring data report. Results of sampling program for year 2002, prepared for the  
3228 Ministry of the Environment, province of British Columbia, Nanaimo, B.C. abstract only  
3229 URL: [http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon\\_farming.htm](http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon_farming.htm).
- 3230 Wright, C., Taekema, B., Burd, B., McGreer, E.R., 2007d. Salmon aquaculture environmental  
3231 monitoring data report. Results of sampling program for year 2003, prepared for the



- 3232 Ministry of the Environment, province of British Columbia, Nanaimo, B.C. abstract only  
3233 URL: [http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon\\_farming.htm](http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon_farming.htm).
- 3234 Wright, C., Taekema, B., Burd, B., McGreer, E.R., 2007e. Salmon aquaculture environmental  
3235 monitoring data report. Results of sampling program for year 2004, prepared for the  
3236 Ministry of the Environment, province of British Columbia, Nanaimo, B.C. abstract only  
3237 URL: [http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon\\_farming.htm](http://www.elp.gov.bc.ca/epd/industrial/aquaculture/salmon_farming.htm)
- 3238 Yeats, P.A., 2002. Trace metal tracers of fish farm wastes. 2002. In: Hargrave, B.T., (Ed.).  
3239 Environmental Studies for Sustainable Aquaculture (ESSA): 2002 Workshop Report.  
3240 Canadian Technical Report of Fisheries and Aquatic Sciences 2411, 82-85.
- 3241 Yunker, M.B., 2000. Sediment PAH signatures in the IONA receiving environment, in: Greater  
3242 Vancouver Regional District, (Ed.), Development of a Receiving Environment  
3243 Monitoring Approach to Liquid Waste Management: Progress Workshop 2, Chapter 3-  
3244 23 pp.
- 3245 Yunker, M.B., Macdonald, R.W., Brewer, R., Sylvestre, S., Tuominen, T., Sekela, M., Mitchell,  
3246 R.H., Paton, D.W., Fowler, B.R., Gray, C., Goyette, D., Sullivan, D., 2000. Assessment  
3247 of natural and anthropogenic hydrocarbon inputs using PAHs as tracers. The Fraser  
3248 River Basin and Strait of Georgia (1987-1997), Aquatic and Atmospheric Sciences  
3249 Division, Environmental Conservation Branch, Pacific and Yukon Region, Environment  
3250 Canada, Vancouver, B. C., 128 pp.
- 3251 Yunker, M.B., Macdonald, R.W., Goyette, D., Paton, D.W., Fowler, B.R., Sullivan, D., Boyd, J.,  
3252 1999. Natural and anthropogenic inputs of hydrocarbons to the Strait of Georgia. Science  
3253 of the Total Environment 225, 181-209.

- 3254 Zacharias, M.A., Howes, D.E., 1998. An analysis of marine protected areas in British Columbia,  
3255 Canada, using a marine ecological classification. *Natural Areas Journal* 18, 4-13.
- 3256 Zacharias, M.A., Howes, D.E., Harper, J.R., Wainwright, P., 1998a. The British Columbia  
3257 marine ecosystem classification: Rationale, development, and verification. *Coastal*  
3258 *Management* 26, 105-124.
- 3259 Zacharias, M.A., Howes, D., Ogborne, C., 1998b. A biophysical habitat classification for  
3260 intertidal environments in the Strait of Georgia, in: Levings, C.D., Pringle, J.D., Aikens,  
3261 F., (Eds.), *Approaches to Marine Ecosystem Delineation in the Strait of Georgia*.  
3262 *Proceedings from a DFO Workshop, Sidney, B.C. November, 1997. Canadian Technical*  
3263 *Report of Fisheries and Aquatic Sciences* 2247, 105-111.
- 3264 Zacharias, M.A., Morris, M.C., Howes, D.E., 1999. Large scale characterization of intertidal  
3265 communities using a predictive model. *Journal of Experimental Marine Biology and*  
3266 *Ecology* 239, 223-242.
- 3267 Zacharias, M.A., Roff, J.C., 2001. Explanations of patterns of intertidal diversity at regional  
3268 scales. *Journal of Biogeography* 28, 471-483.
- 3269 Ziervogel, K., Forster, S., 2006. Do benthic diatoms influence erosion thresholds on coastal  
3270 subtidal sediments? *Journal of Sea Research* 51, 43-53.
- 3271 Zis, T., Ronningen, V., Scrosat, R., 2004. Minor improvement for intertidal seaweeds and  
3272 invertebrates after acid mine drainage diversion at Britannica Beach, Pacific Canada.  
3273 *Marine Pollution Bulletin*, 48, 1040-4047.
- 3274 Zorn, M.E., Lalonde, S.W., Gingras, M.K., Pemberton, S.G., Konhauser, K.O., 2006. Microscale  
3275 oxygen distribution in variousl invertebrate burrow walls. *Geobiology* 4, 137-145.
- 3276

3277 **Figure Captions**

3278

3279 Figure 1. The Strait of Georgia, including depth contours from multibeam imagery (see also Fig.  
3280 3), locations of important geographic units and discharge sources described herein, and  
3281 theoretical boundaries of north, middle and southern oceanographic regimes within the main  
3282 basin.

3283

3284 Figure 2. Physical parameters used to develop ecounits (Modified from the Ministry of  
3285 Sustainable Resource Management (<http://ilmbwww.gov.bc.ca/risc/>). Substrate = mud, sand,  
3286 hard (M,S,H); Exposure = high, moderate, low (H,M,L); Current = High >3knots, low <3 knots  
3287 (H,L); Slope = Flat 0-5%, sloping 5-20%, Steep >20% (F,S,S); Depth = Shallow 0-20m; photic  
3288 20-50m, mid-depth 50-200m, deep 200-1000m; Temperature = warm 9-15°C, cold <9°C; Relief  
3289 = low 0-1, medium 2, high 3-4. For example: ecounit = M/L/L/F/M/C/L: Substrate = mud;  
3290 Exposure = low; Current = low; Slope = flat; Depth = mid-depth; Bottom Temperature = cold;  
3291 Relief = low.

3292

3293 Figure 3. Multibeam imagery from the southern Strait of Georgia showing bottom relief and  
3294 type, courtesy of Natural Resources Canada, Pacific Geoscience Center, Sidney, BC.

3295

3296 Figure 4. Plot of sediment percent fines (silt/clay <63 µm particle size) to illustrate sediment  
3297 types in the Strait of Georgia (data from Burd, 2006; and courtesy of Natural Resources Canada,  
3298 Pacific Geoscience Center, Sidney, BC).

3299

3300 Figure 5. MERIS satellite taken 2007/07/10 (copyright, European Space Agency). True colour  
3301 image, Courtesy of Jim Gover and Stephanie King, Institute of Ocean Sciences, Canadian  
3302 Department of Fisheries and Oceans, Sidney, BC.

3303

3304 Figure 6. Shorekeepers' Program sites in the Strait of Georgia, BC.

3305 (<http://www.shim.bc.ca/atlas/esk/main.htm>).

3306

3307 Figure 7. Habitat (beach) suitability maps for Pacific oysters and Manila clams and a  
3308 corresponding area map for kelp and eelgrass habitat as generated by the Internet. Framework  
3309 Mapping tool provided by the Provincial Ministry of the Environment (<http://maps.gov.bc.ca/>).

3310

3311 Table 1. Gross features of the Strait of Georgia, B.C. (from England et al. 1996, Thomson 1998,  
 3312 and Thomson and Foreman 1998).

<b>Feature</b>	<b>Measure</b>
Surface Area	6515 km <sup>2</sup>
Area at 100m depth	4374 km <sup>2</sup>
Volume	1050 km <sup>3</sup>
Mean Depth	155m
Maximum Depth	420m (S Texada Island)
Annual Mean Runoff	5650±3500 m <sup>3</sup> /s
Drainage Area	286,890 km <sup>2</sup>
Sill Depth – Haro Strait	90m
Sill Depth – Rosario Strait	50m
Summer Basin Flushing	50-75 days
Winter Basin Flushing	100-200 days

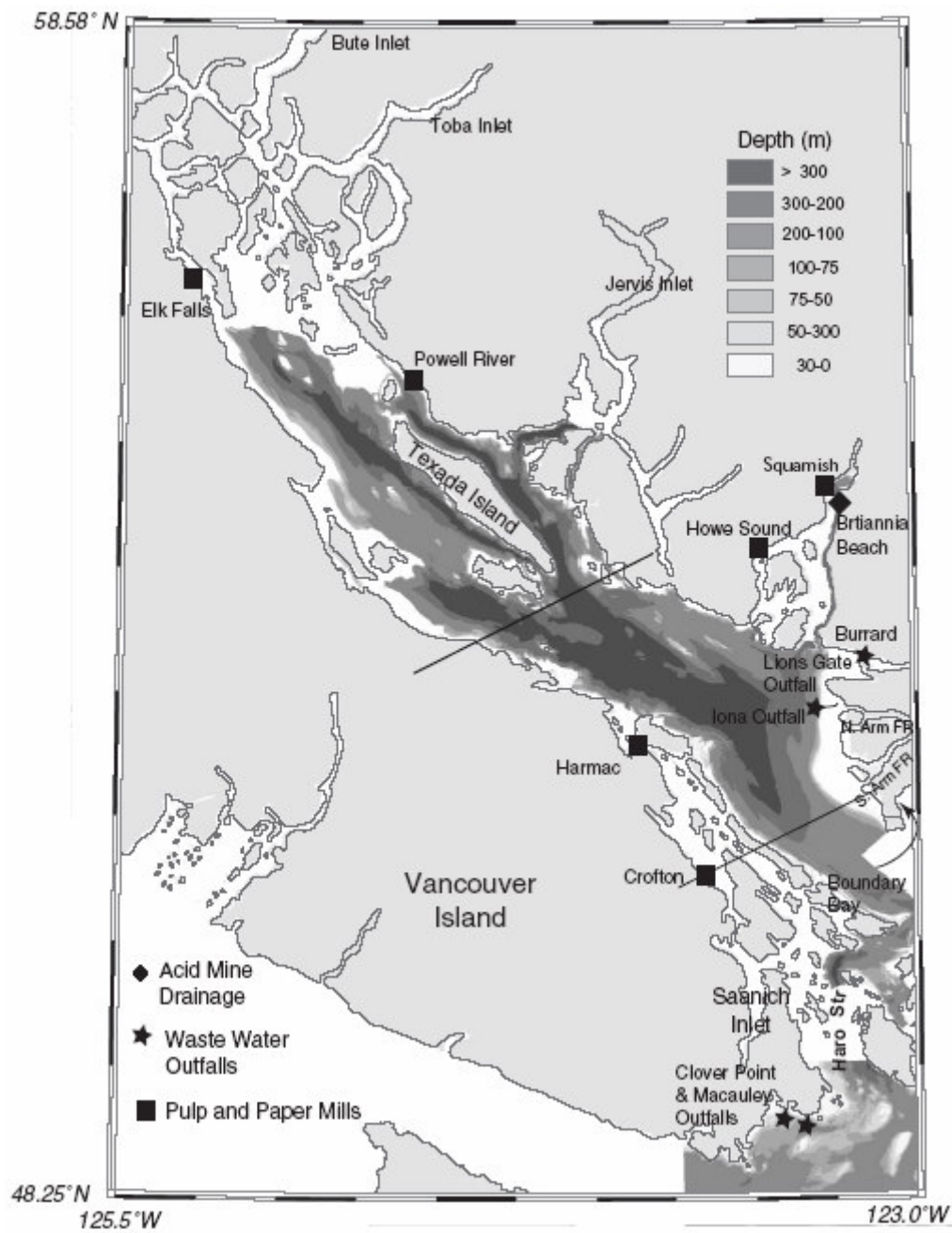
3313

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3315

3316 Figure 1

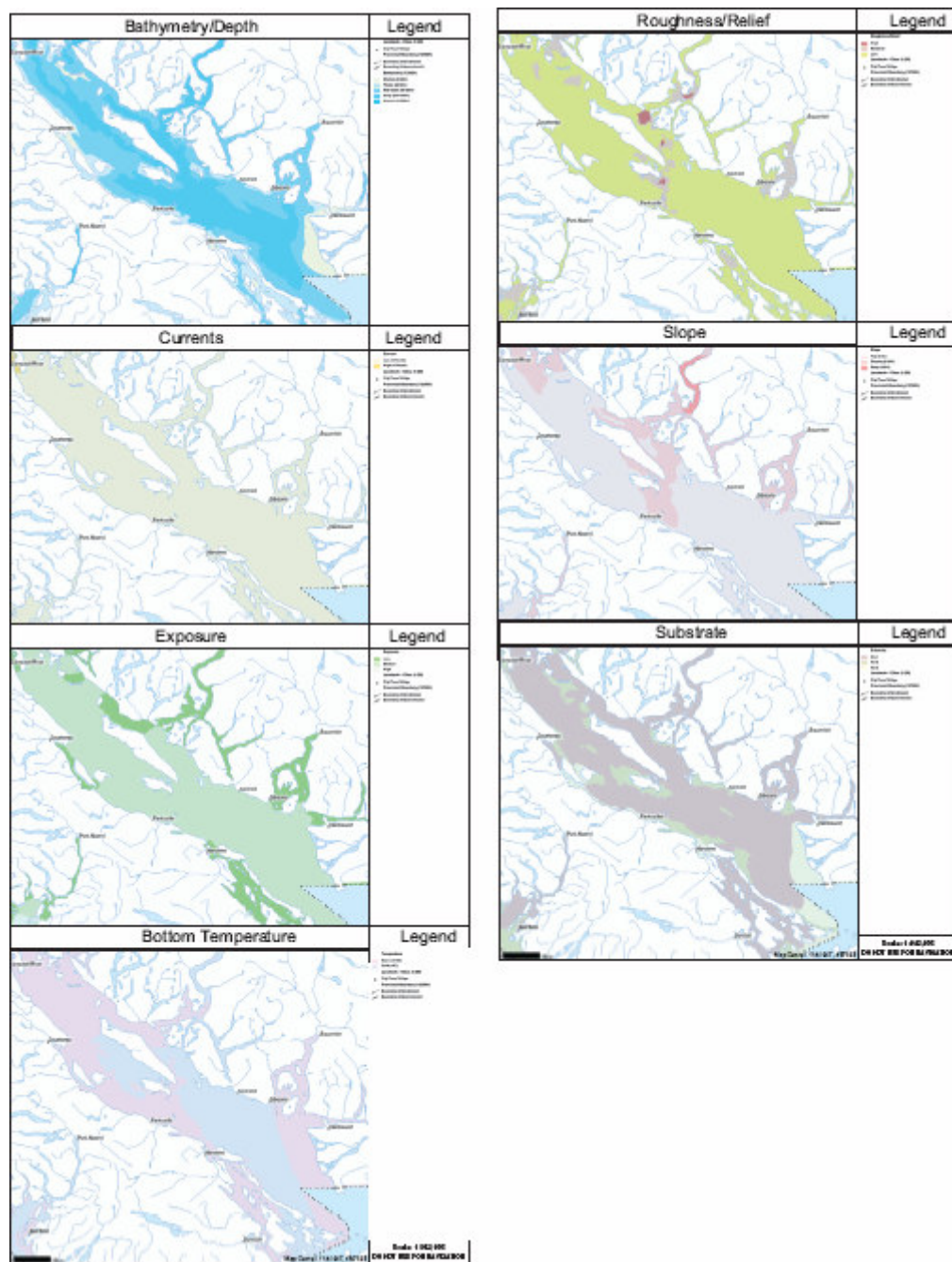
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3319 Figure 2

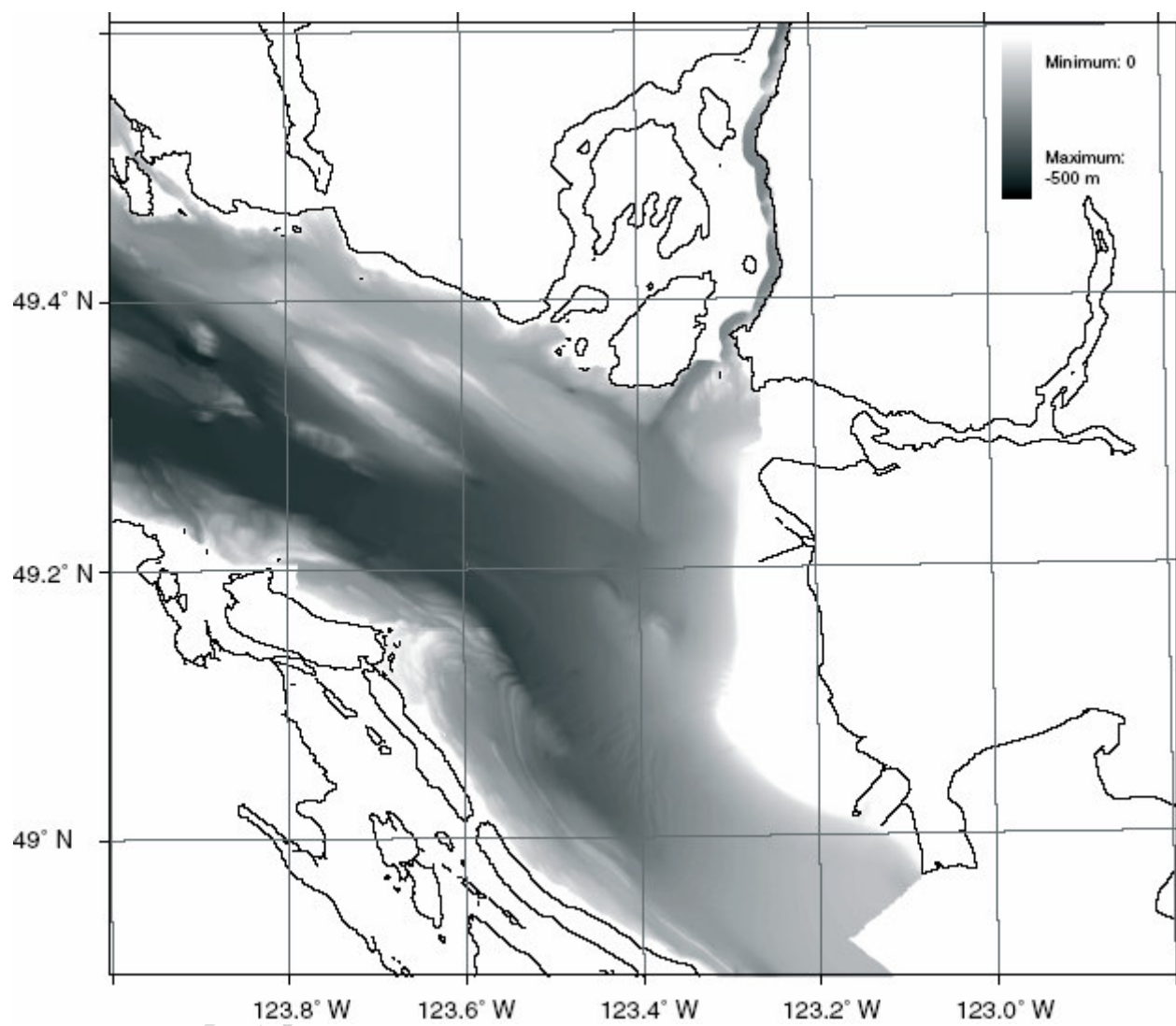
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3321

3322 Figure 3

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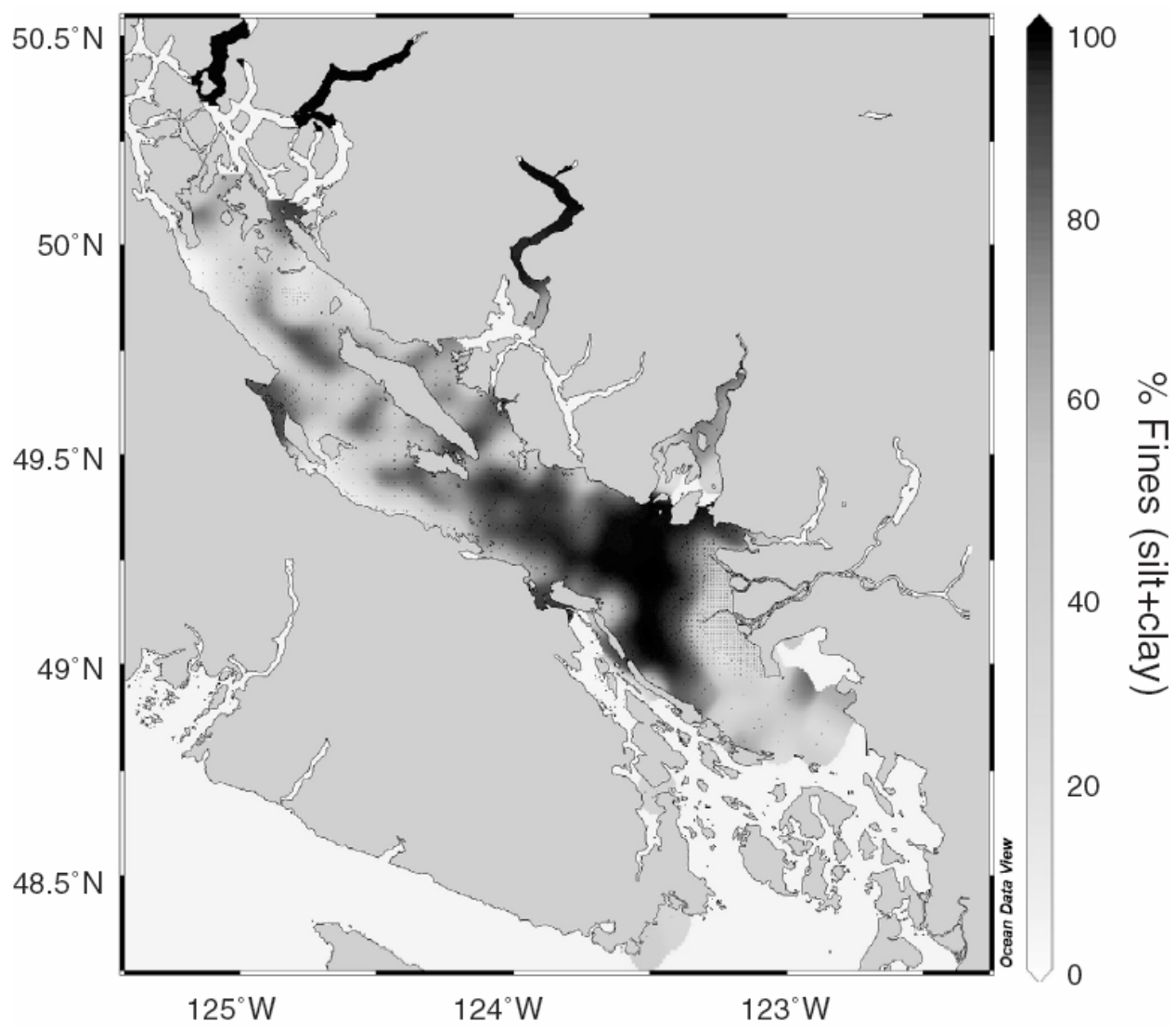
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3325 Figure 4

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3328 Figure 5

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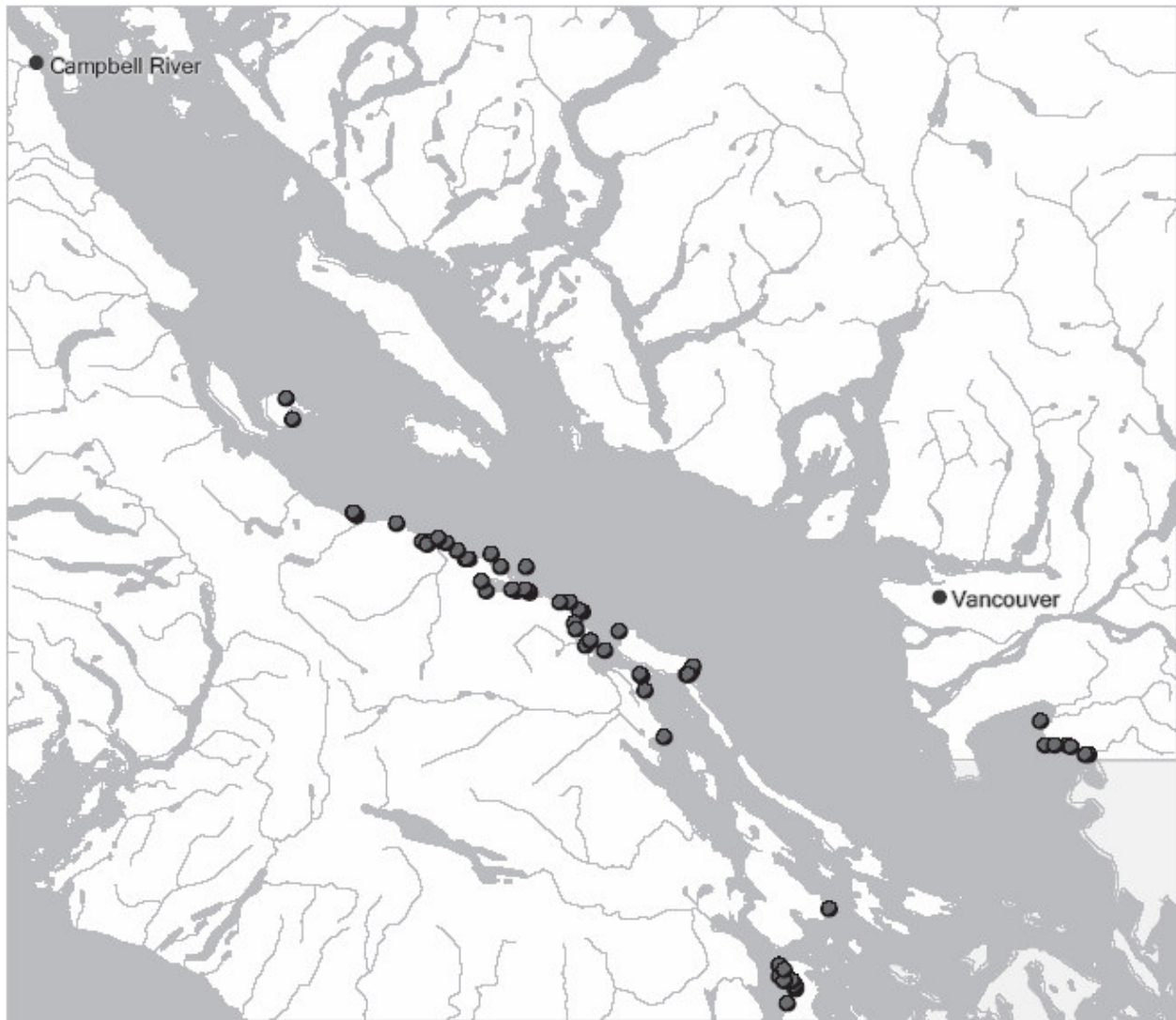


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3331 Figure 6

3332

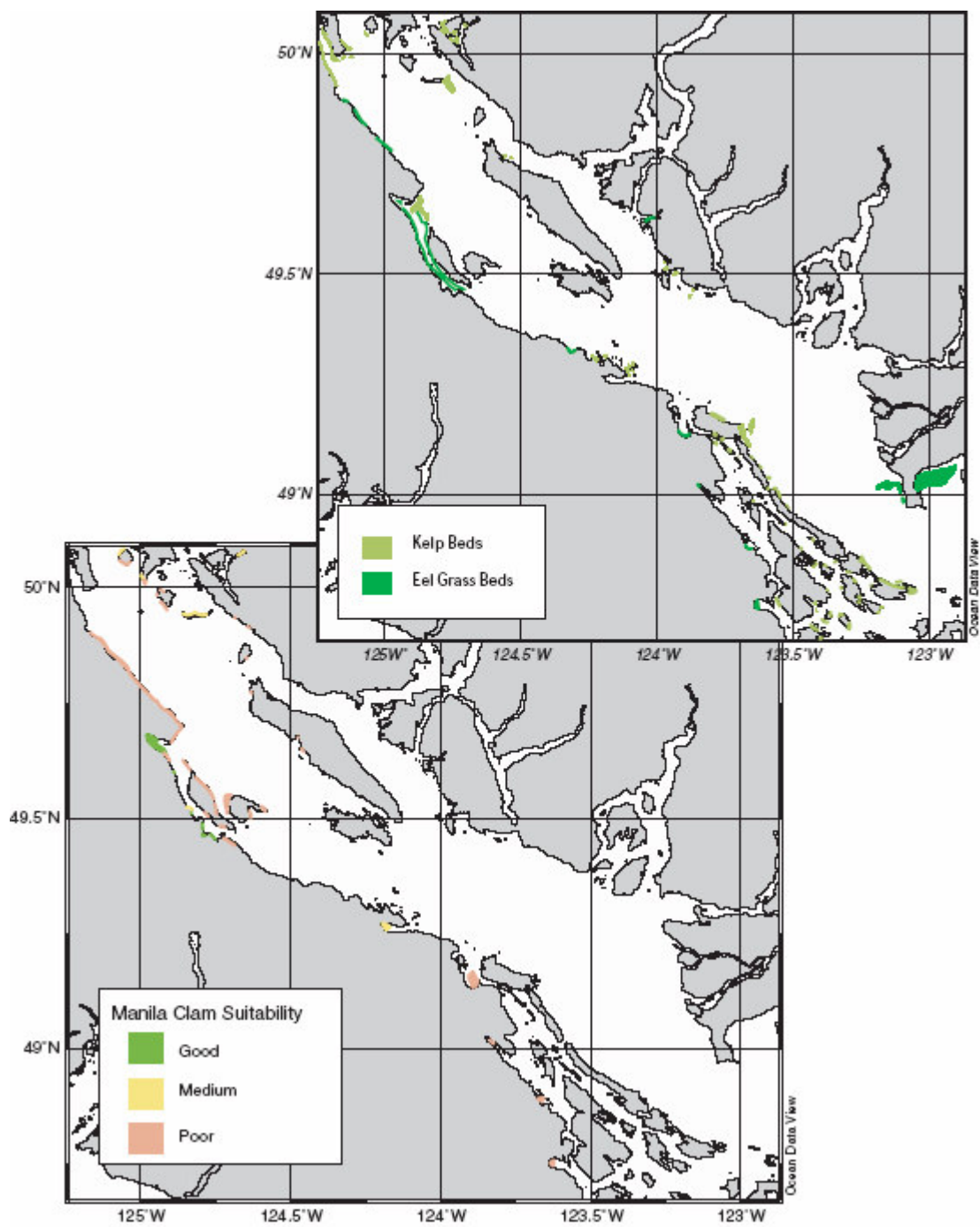


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3334 Figure 7

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